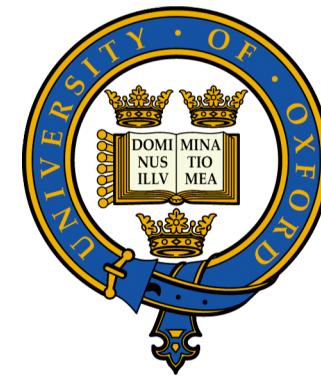


First Run II Measurement of the W Boson Mass by CDF



Oliver Stelzer-Chilton
University of Oxford



Particle Physics Seminar
CERN

March 20th, 2007

Outline

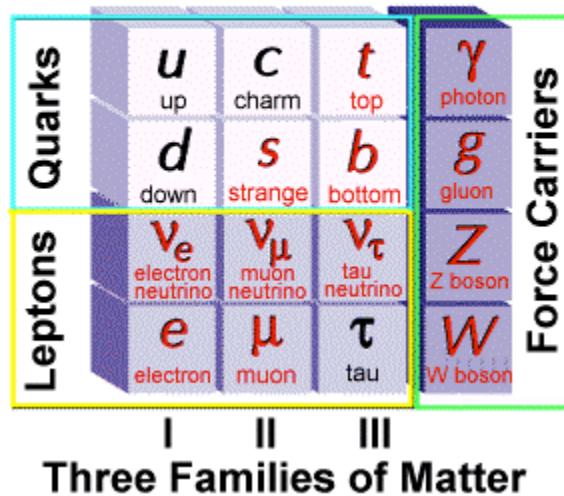
1. Motivation
2. W Production at the Tevatron
3. Analysis Strategy
4. Detector Calibration
 - Momentum Scale
 - Energy Scale
 - Recoil
5. Event Simulation
6. Results
7. Conclusions



The W Boson and the Standard Model

- 1930's: Fermi explains nuclear β -decay as 4-point interaction
- 1960's: Glashow, Weinberg and Salam
 - unify electromagnetic and weak interaction
 - explain interaction by exchange of massive vector bosons

Elementary Particles



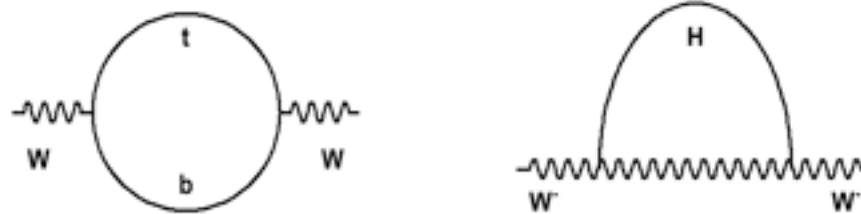
- Became foundation of the Standard Model
- W boson mass is fundamental parameter

Introduction

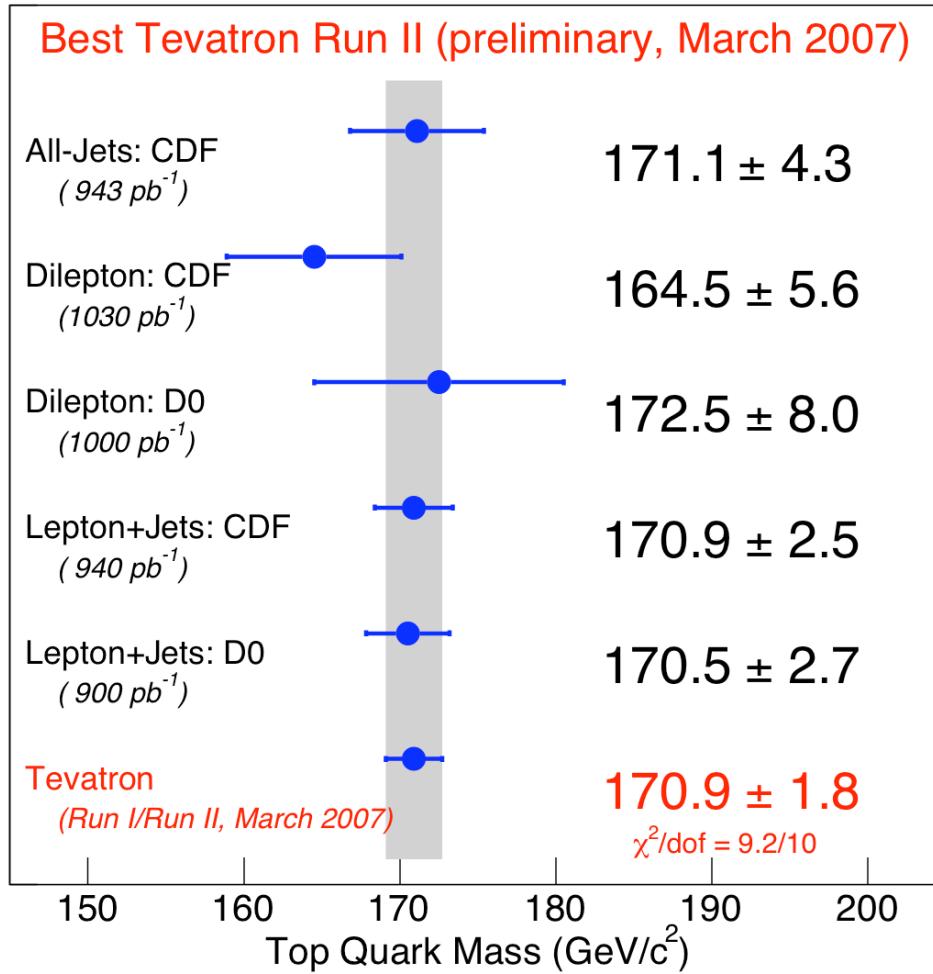
- Derive W mass from precisely measured electroweak quantities

$$m_W^2 = \frac{\pi \alpha_{em}}{\sqrt{2} G_F \sin^2 \theta_W (1 - \Delta r)}$$

- where $M_W = M_Z \cos \theta_W$
- $\alpha_{EM}(M_Z) = 1/127.918(18)$
- $G_F = 1.16637(1) \cdot 10^{-5} \text{ GeV}^{-2}$
- $M_Z = 91.1876(21) \text{ GeV}$
- Δr : radiative corrections dominated by tb and Higgs loop



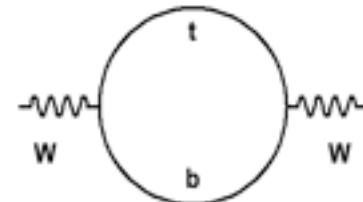
Measured Top Mass



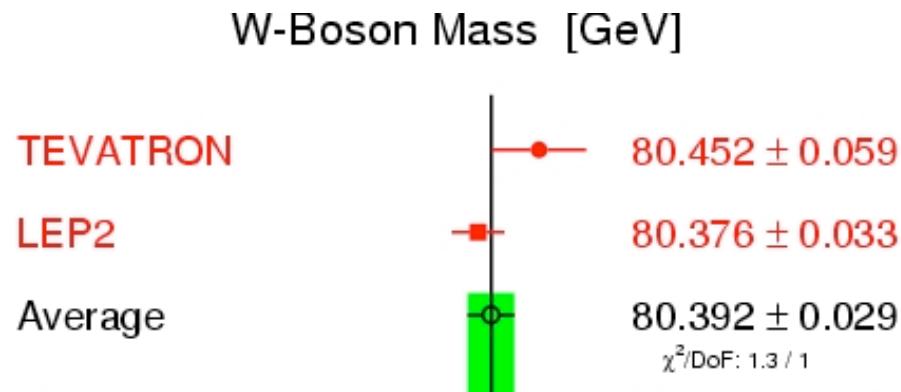
New Tevatron average (last week): Top mass now measured to 1.8 GeV
<http://tevewwg.fnal.gov/top>

Motivation

Current top mass uncertainty 1.1% (1.8 GeV)
→ contributes 0.014 % (11 MeV) to δM_W



Before Winter 2007: W mass uncertainty 0.036% (29 MeV)

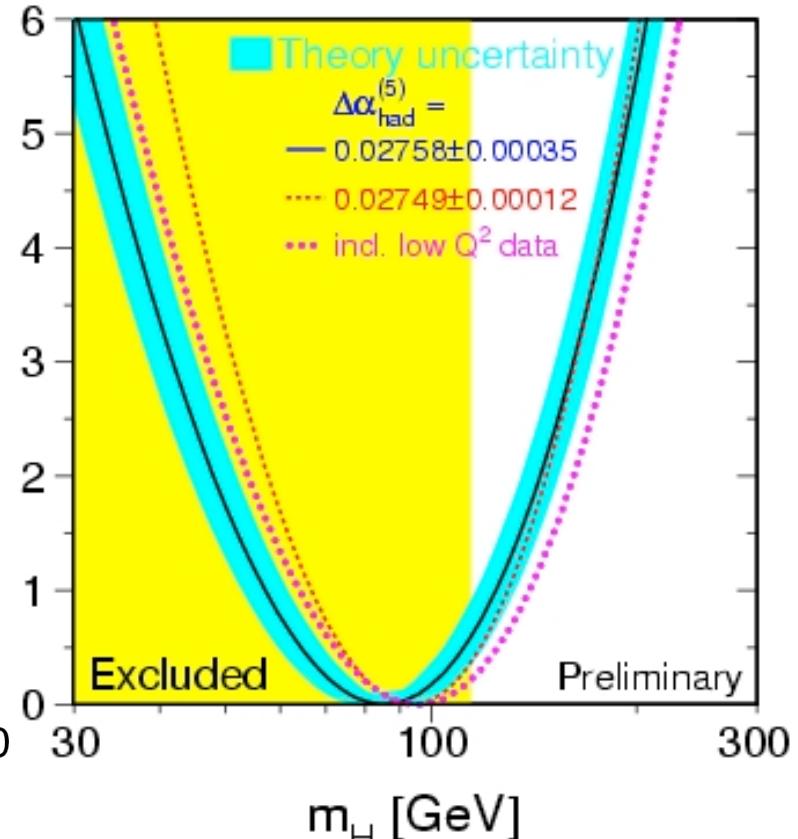
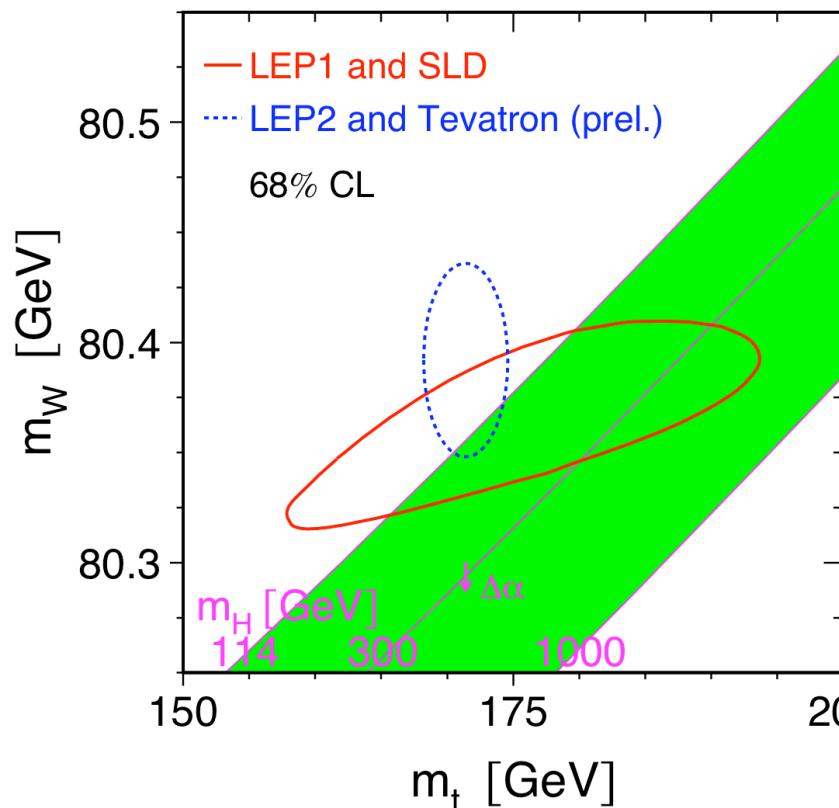


- Progress on W mass uncertainty now has the biggest impact on Higgs mass constraint
- With improved precision also sensitive to possible exotic radiative corrections



Higgs Mass Prediction

Before Winter 2007



Predicted Higgs mass from W loop corrections (LEP EWWG):

$$m_H = 85^{+39}_{-28} \text{ GeV} (\text{ < } 166 \text{ GeV at 95% CL})$$

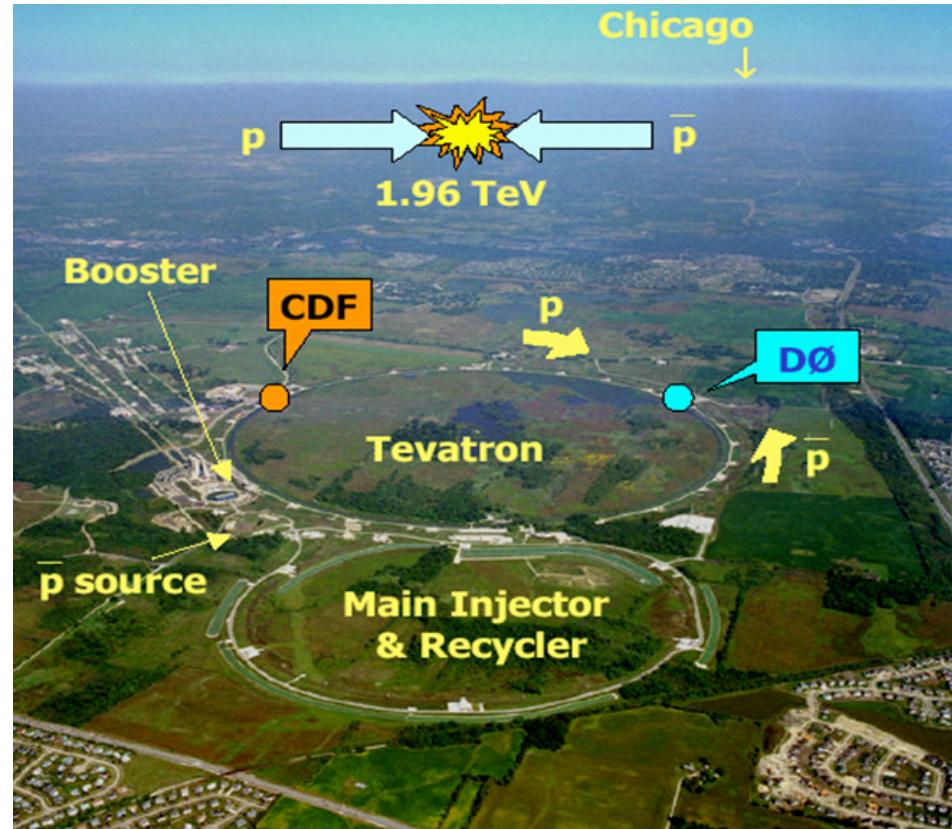
direct search from LEP II: $m_H > 114.4$ GeV

<http://lepewwg.web.cern.ch/LEPEWWG/>

Analysis Strategy

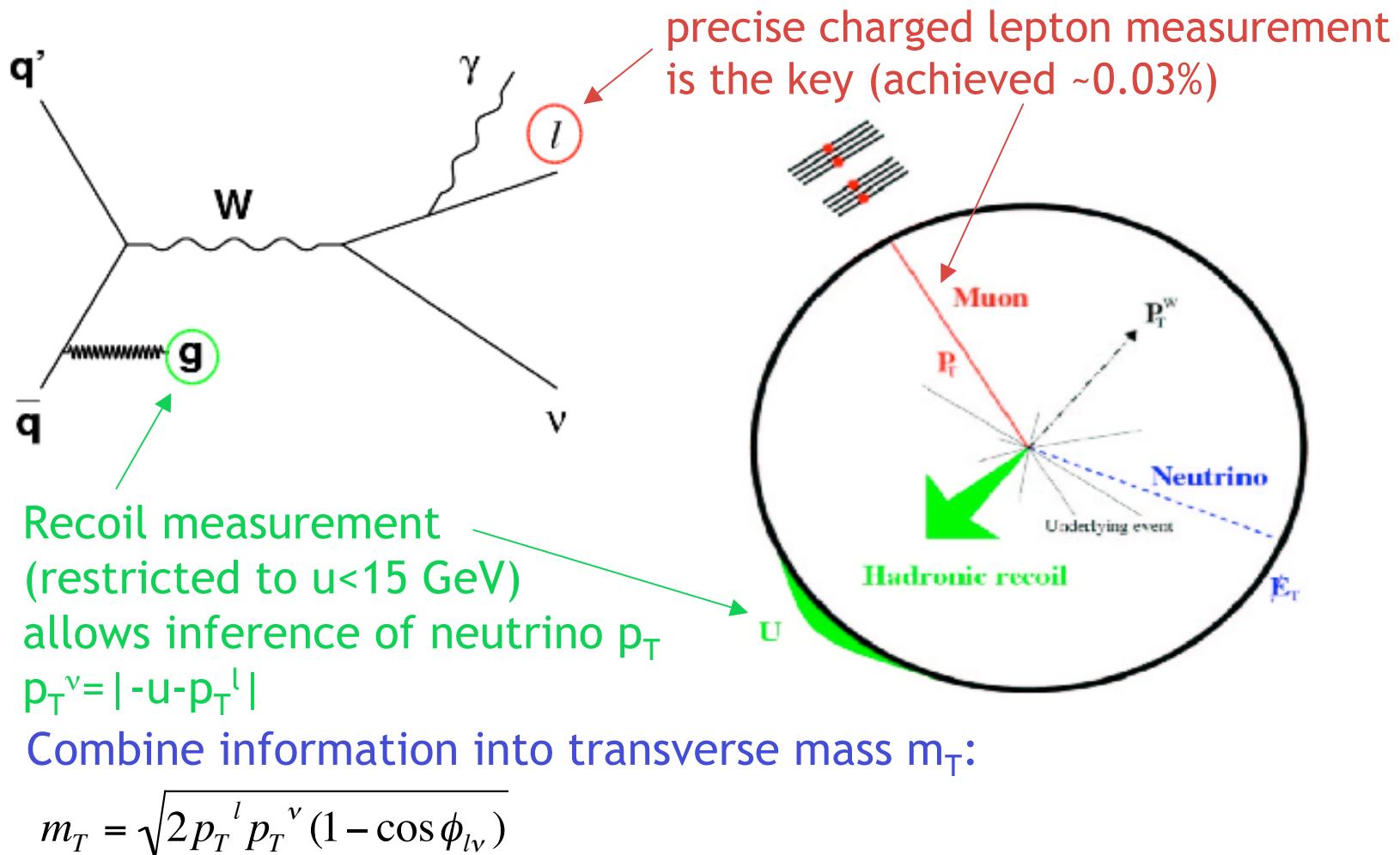
Tevatron Collider

- Tevatron is a proton antiproton collider with ~1 TeV per beam
- Currently the only place in the world where W and Z bosons can be produced directly
- 36 p and pbar bunches, 396 ns between bunch crossing, $E_{CM}=1.96 \text{ TeV}$

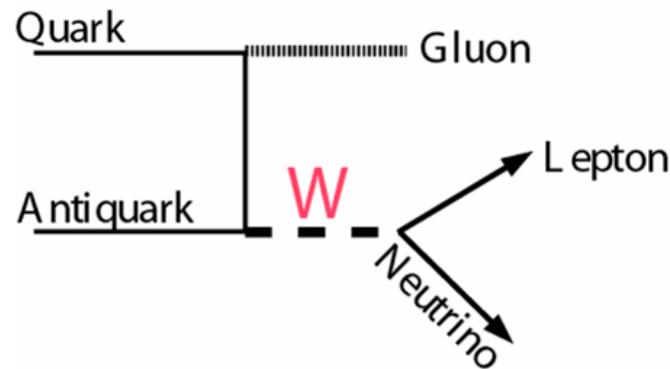


W Production

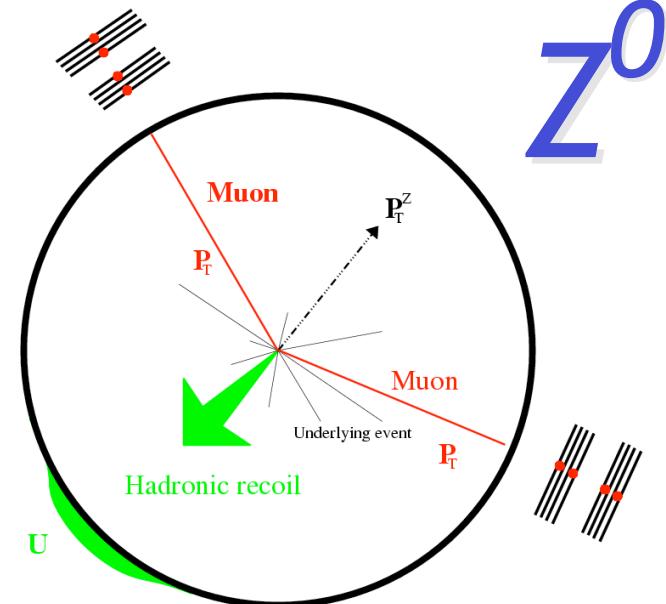
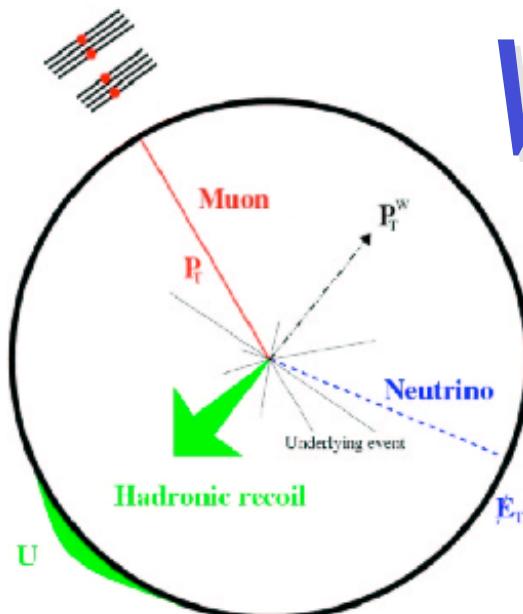
Quark-antiquark annihilation dominates (80%)



W/Z Boson Production at the Tevatron

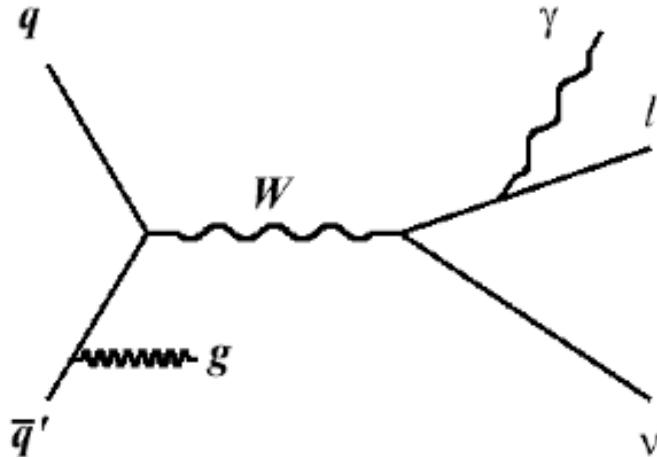


- Initial state QCD radiation appears as soft “hadronic recoil” in calorimeter
- Pollutes W mass information
fortunately $p_T^W \ll M_W$

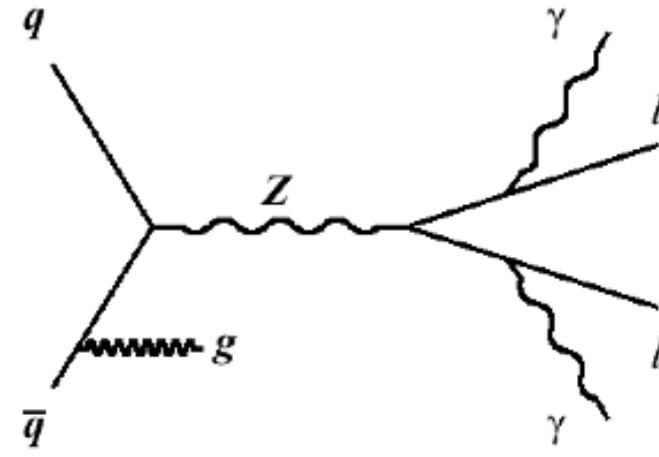


- Can use $Z \rightarrow ll$ decays to calibrate recoil model

W/Z Boson Production and Decay



$$\sigma(W \rightarrow l\nu) = 2775 \text{ pb}$$



$$\sigma(Z \rightarrow ll) = 254.9 \text{ pb}$$

From the high p_T lepton triggers ($p_T > 18 \text{ GeV}$)

After event selection
 $E_T(l, \nu) > 30 \text{ GeV}$

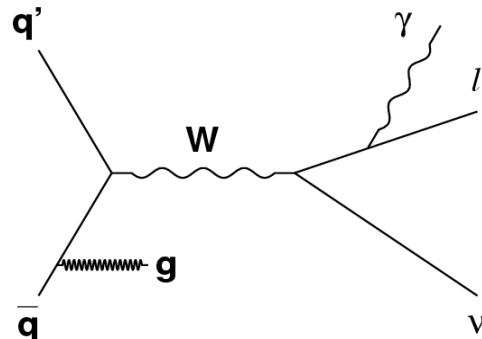
After event selection
 $E_T(l) > 30 \text{ GeV}$

51,128 $W \rightarrow \mu\nu$ candidates
63,964 $W \rightarrow e\nu$ candidates

4,960 $Z \rightarrow \mu\mu$ candidates
2,919 $Z \rightarrow ee$ candidates

Measurement Strategy

W mass is extracted from transverse mass, transverse momentum and transverse missing energy distribution



Detector Calibration

- Tracking momentum scale
- Calorimeter energy scale
- Recoil

Data

Binned likelihood fit

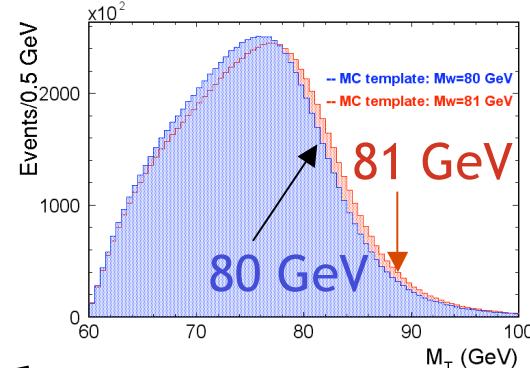
W Mass

Fast Simulation

- NLO event generator
- Model detector effects

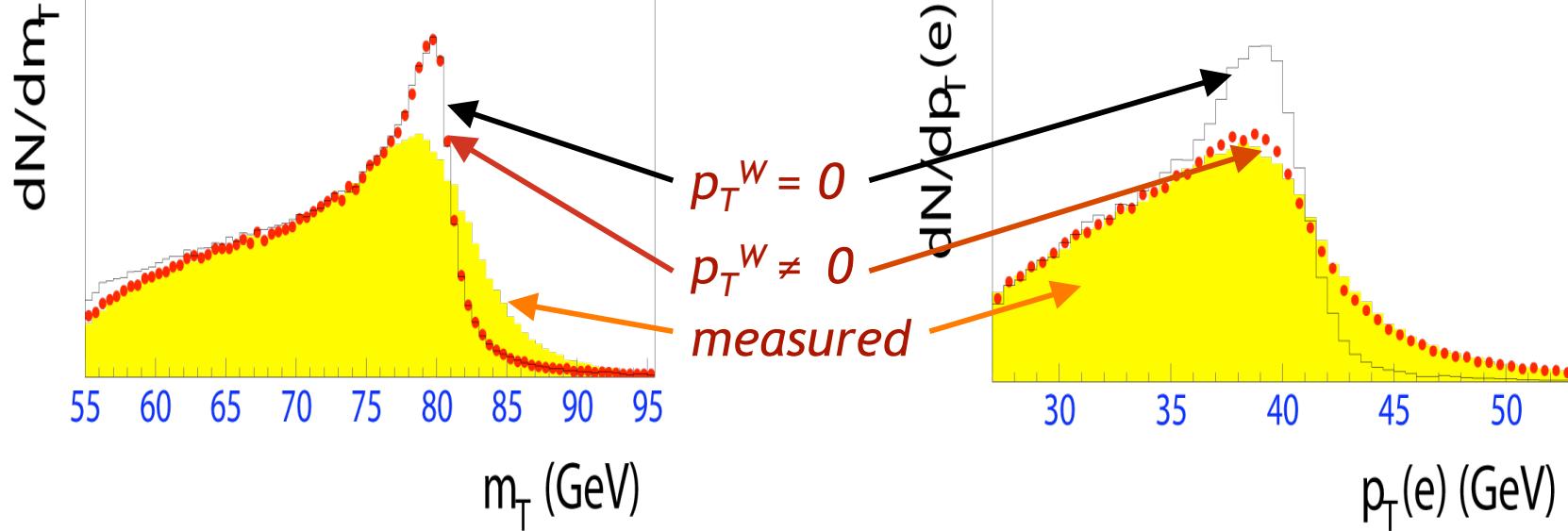


W Mass templates



+ Backgrounds

W Mass Measurement



m_T

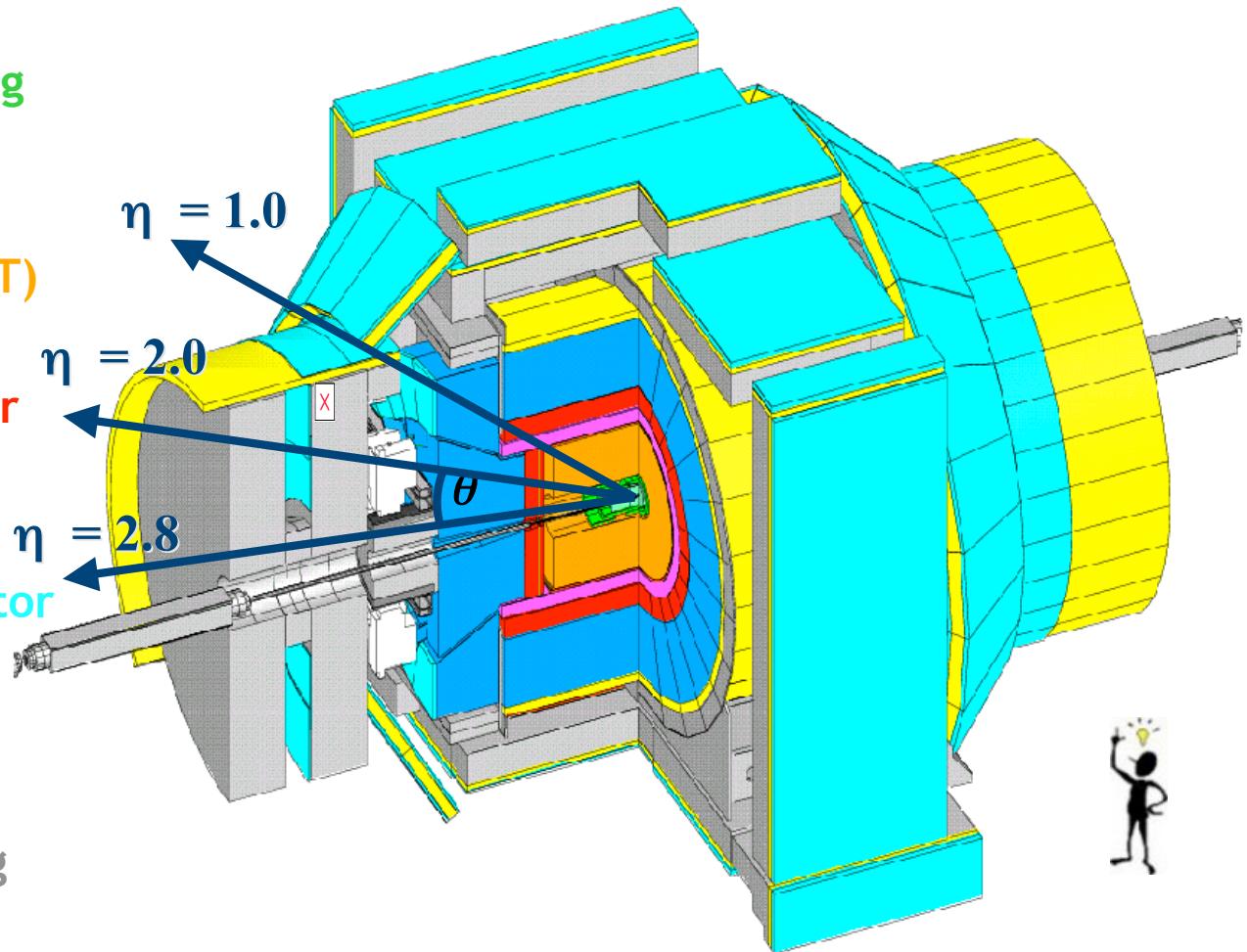
- Insensitive to p_T^W to 1st order
- Reconstruction of p_T^V sensitive to hadronic response and multiple interactions

p_T

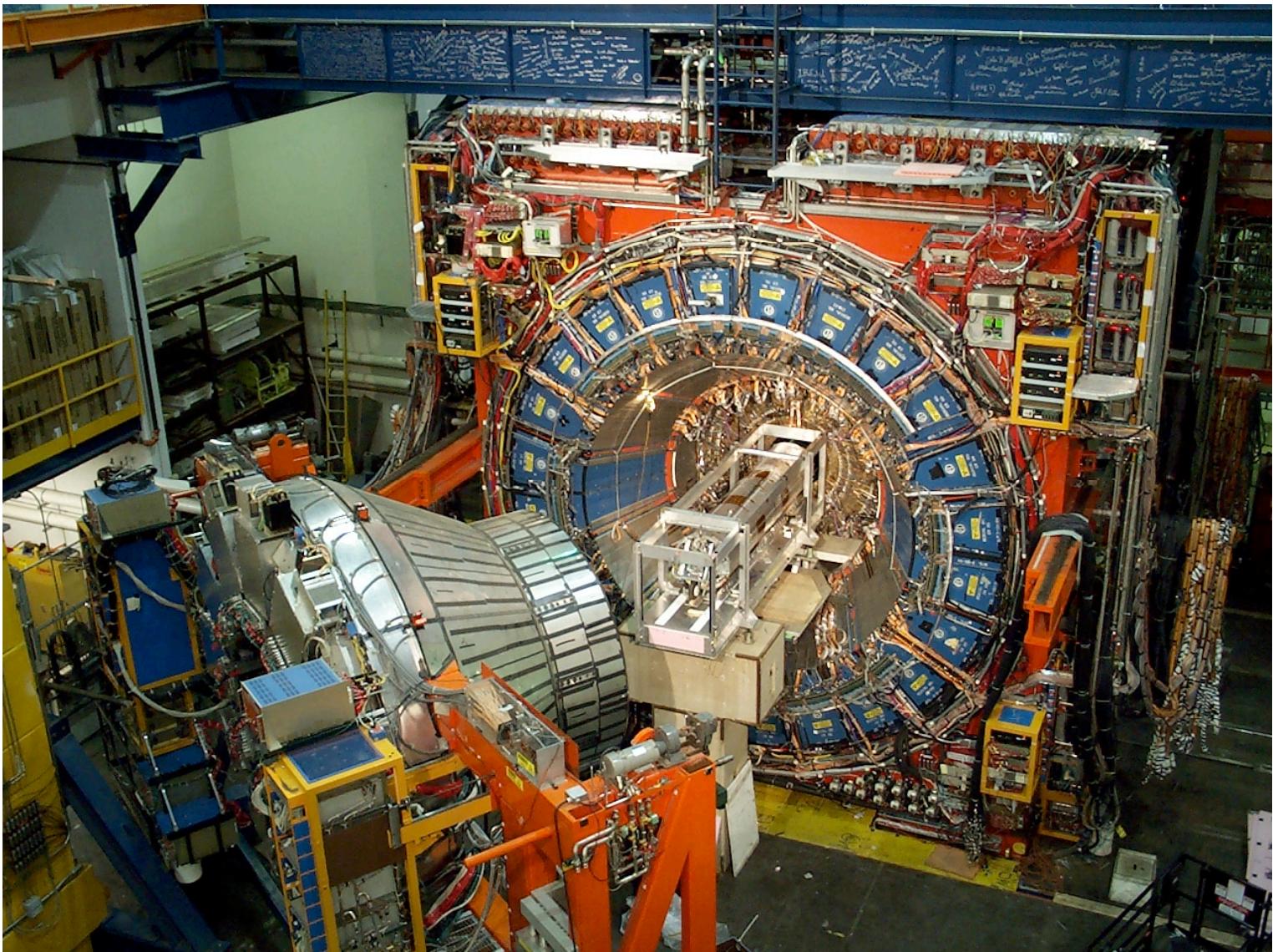
- Less sensitive to hadronic response modeling
- Sensitive to W production dynamics

CDF II Detector

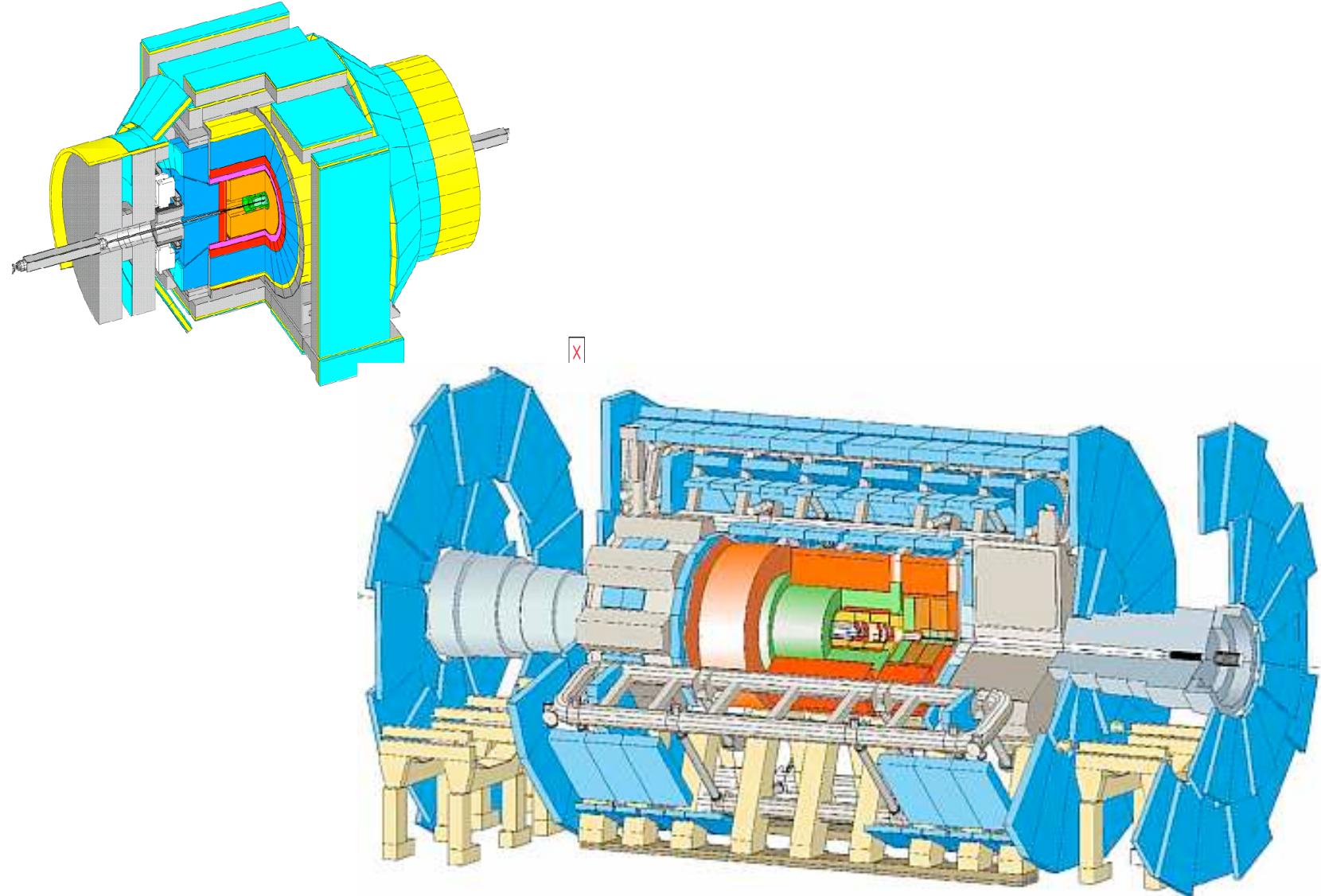
- Silicon tracking detectors
- Central drift chambers (COT)
- Solenoid Coil
- EM calorimeter
- Hadronic calorimeter
- Muon scintillator counters
- Muon drift chambers
- Steel shielding



CDF II Detector

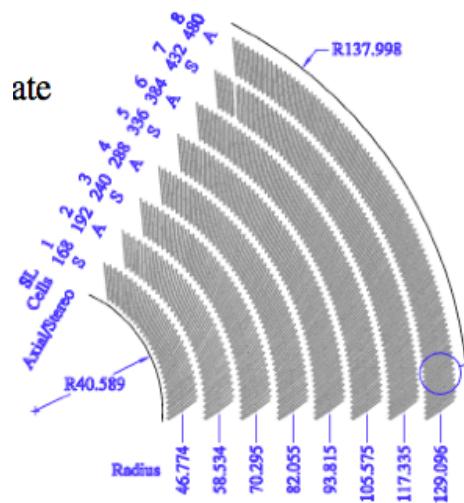


CDF vs ATLAS



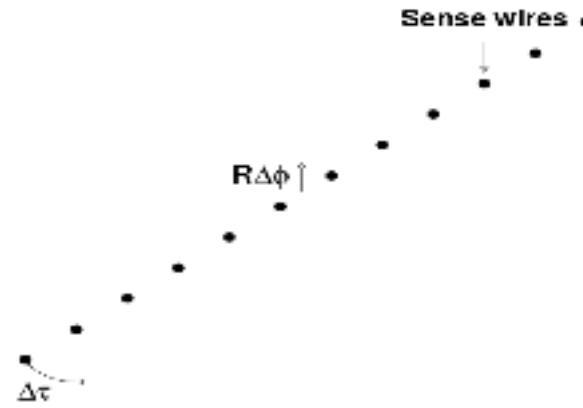
Tracking Momentum Scale Calibration

Tracker Alignment

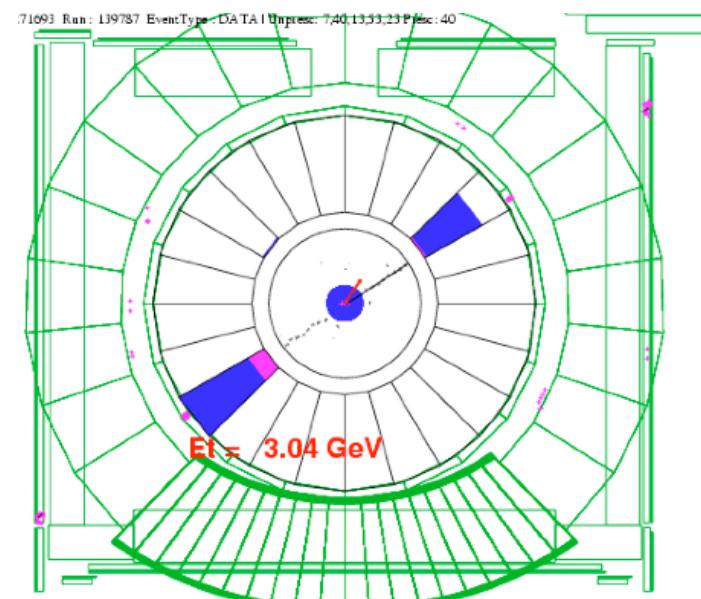


Central Outer Tracker: Open-cell drift chamber

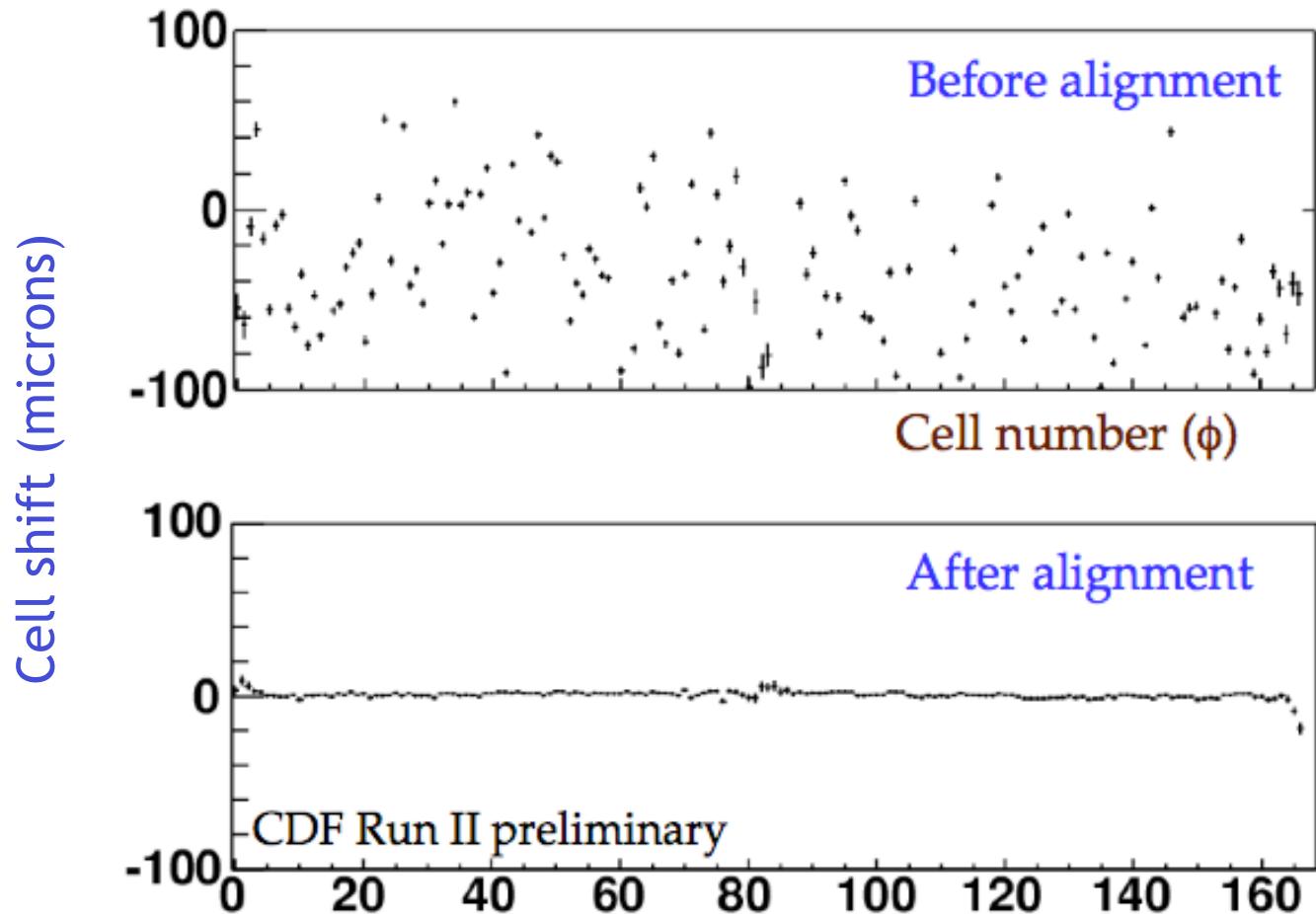
- Measure cell tilts and shifts



- Use clean sample of cosmic rays for cell-by-cell internal alignment
 - Fit COT hits on both sides simultaneously to a single helix



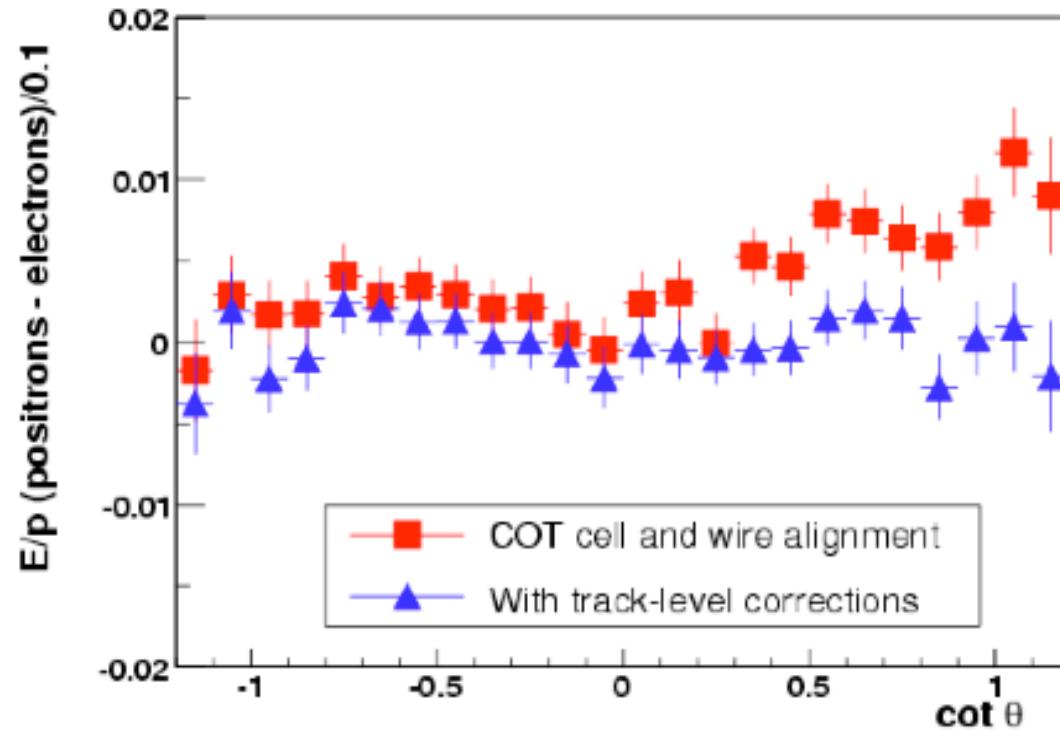
Alignment Example



Final relative alignment of cells $\sim 5\mu\text{m}$ (initial alignment $\sim 50\mu\text{m}$)

Track Level Corrections

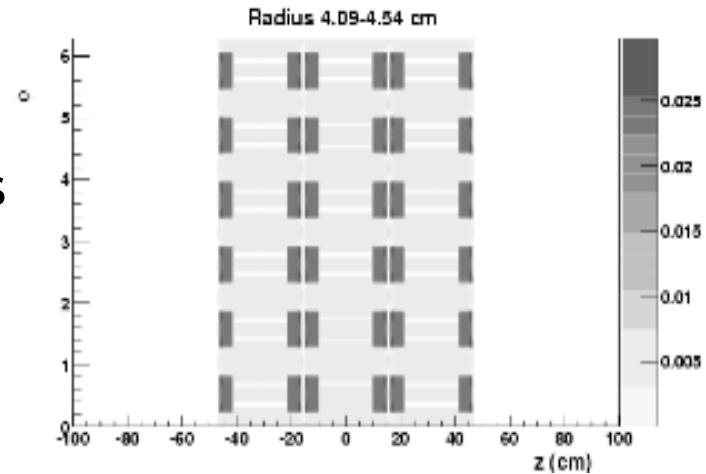
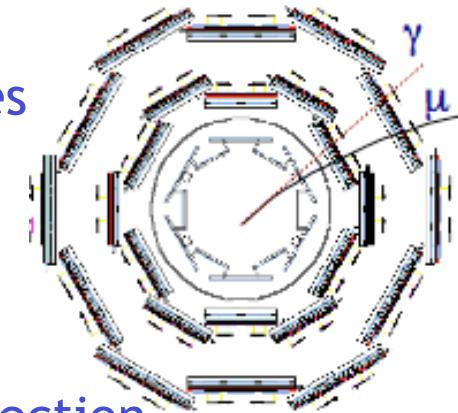
- Determine final track-level curvature corrections from electron-positron E/p difference in $W \rightarrow e\nu$ decays



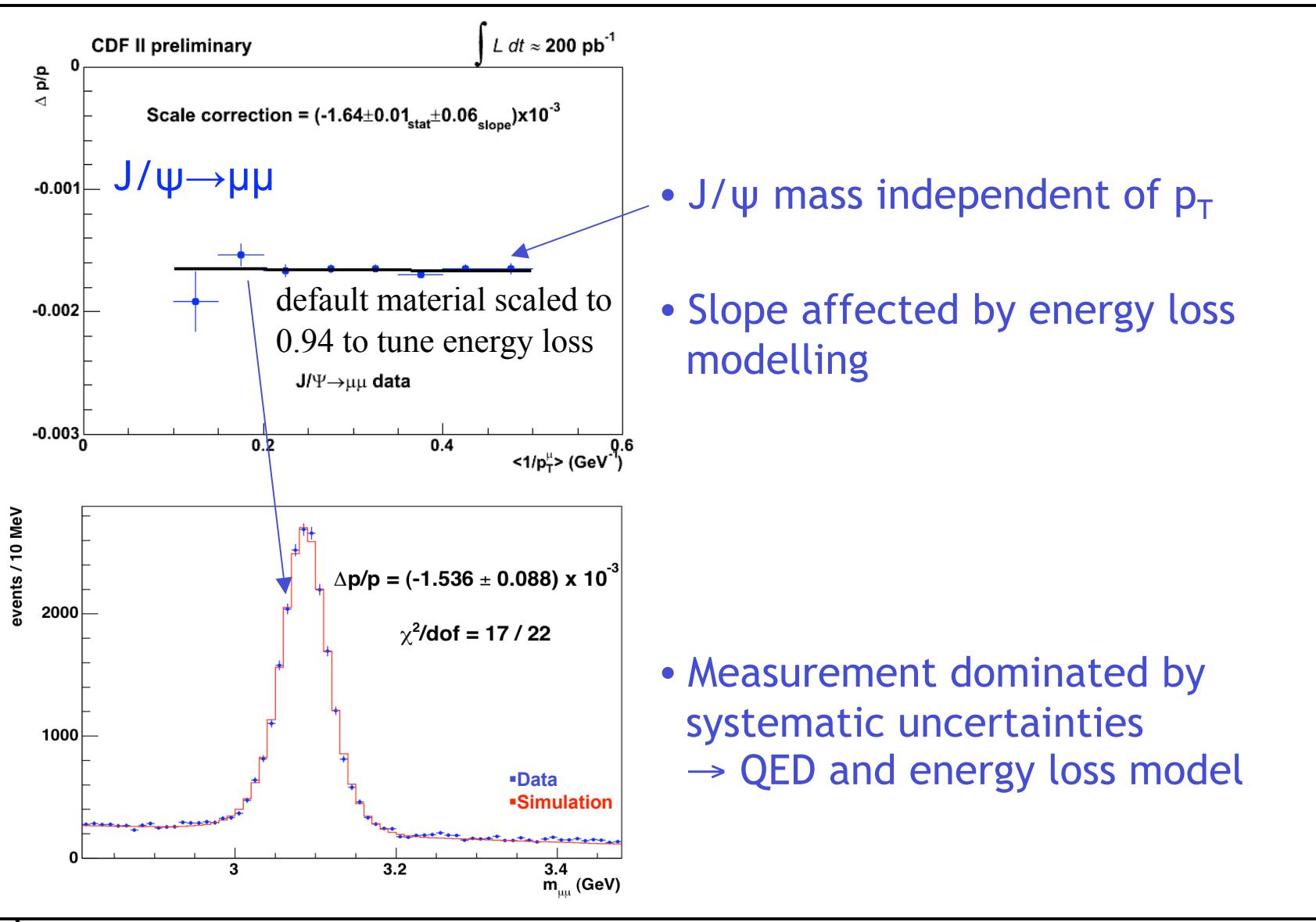
- Statistical uncertainty of track-level corrections leads to systematic uncertainty $\Delta M_W = 6 \text{ MeV}$

Momentum Scale Measurements

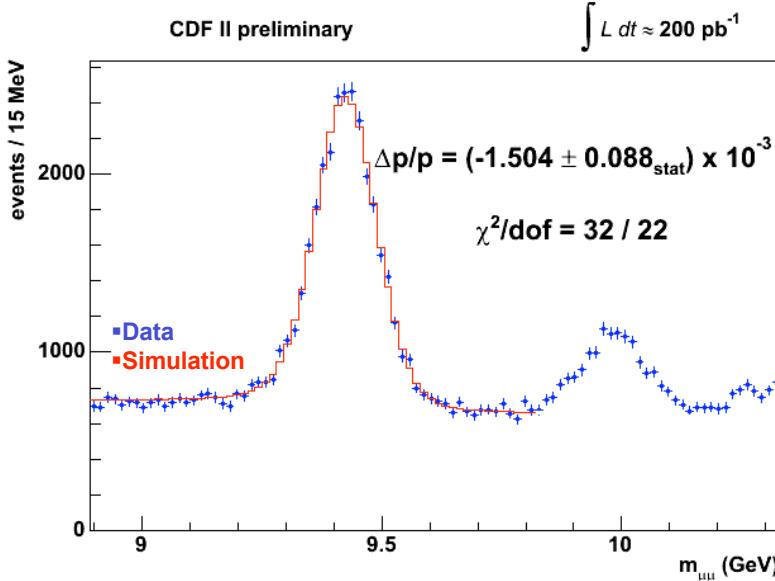
- Template mass fits to $J/\Psi \rightarrow \mu\mu$, $Y \rightarrow \mu\mu$, $Z \rightarrow \mu\mu$ resonances
- Fast simulation models relevant physics processes
 - internal bremsstrahlung
 - ionization energy loss
 - multiple scattering
- Simulation includes event reconstruction and selection
- First principles simulation of tracking
- Detector material model
 - Map energy loss and radiation lengths in each detector layer
(3D lookup table in r , φ and z)
- Overall material scale determined from data



Momentum Scale from J/ψ

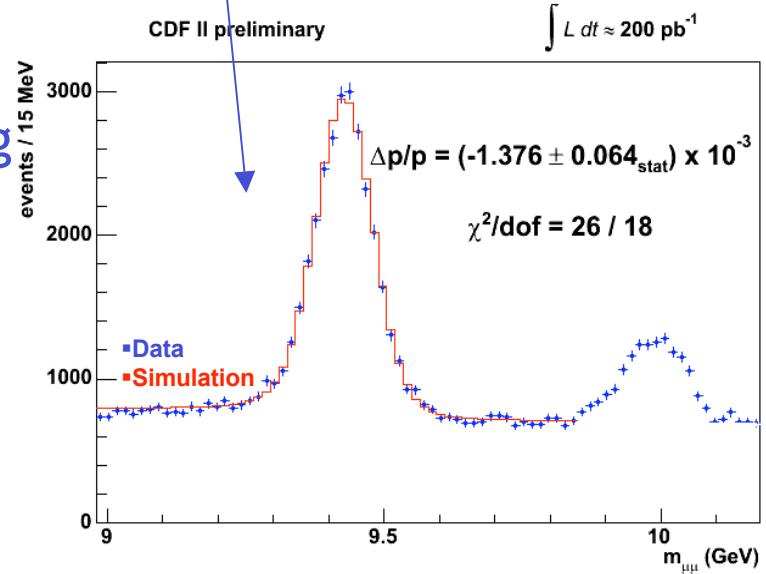


Momentum Scale from Y



- Y provide invariant mass intermediate between J/Ψ and Z 's
- Y are all primary tracks: can be beam-constrained, like W tracks

- Test beam constraint by measuring mass using unconstrained tracks
- Correct by half the difference between fits and take corrections as systematic uncertainty



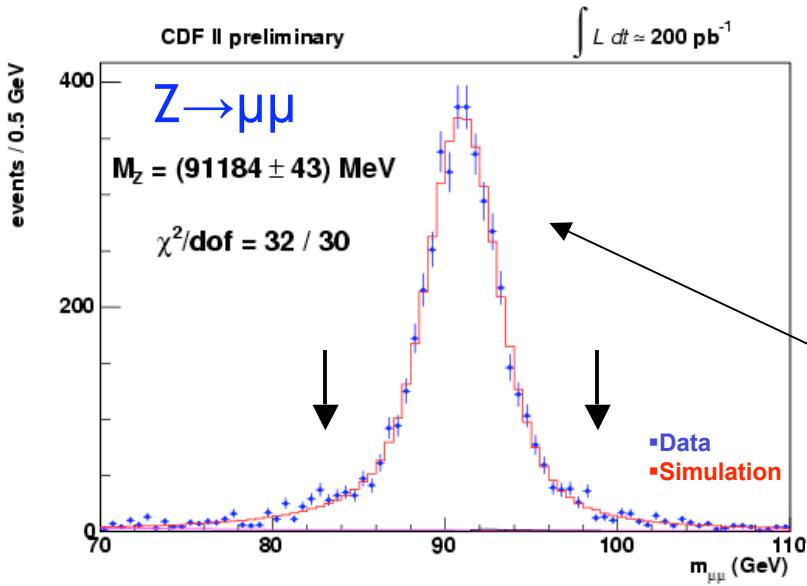
Combined Momentum Scale from Quarkonia

$$\Delta p/p = (-1.50 \pm 0.20) \times 10^{-3}$$

- Systematic uncertainties:

Source	$J/\psi (\times 10^{-3})$	$\Upsilon (\times 10^{-3})$	Common ($\times 10^{-3}$)
QED and energy loss model	0.20	0.13	0.13
Magnetic field nonuniformities	0.10	0.12	0.10
Beam constraint bias	N/A	0.06	0
Ionizing material scale	0.06	0.03	0.03
COT alignment corrections	0.05	0.03	0.03
Fit range	0.05	0.02	0.02
p_T threshold	0.04	0.02	0.02
Resolution model	0.03	0.03	0.03
Background model	0.03	0.02	0.02
World-average mass value	0.01	0.03	0
Statistical	0.01	0.06	0
Total	0.25	0.21	0.17

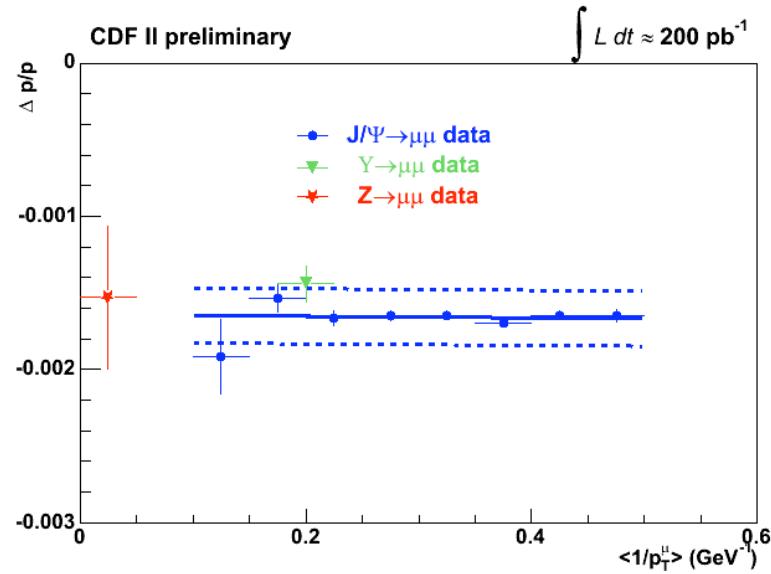
Momentum Scale Cross-Check



Apply momentum scale to $Z \rightarrow \mu\mu$ sample
Z mass in good agreement with PDG (91188 ± 2 MeV)

All momentum scales consistent

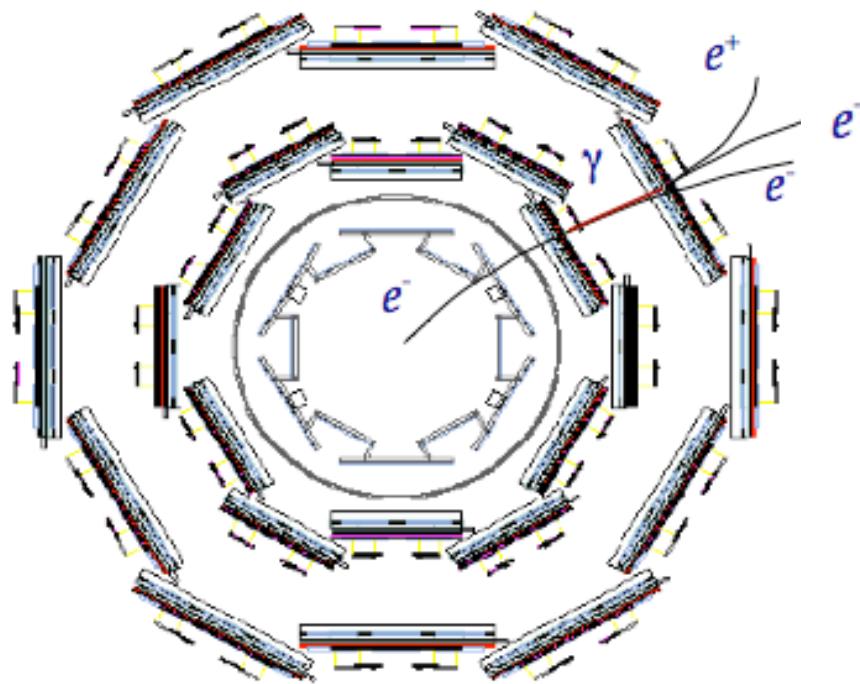
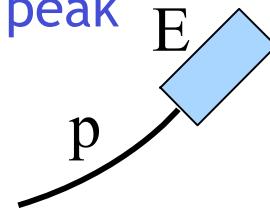
$$\Delta M_W = 17 \text{ MeV}$$



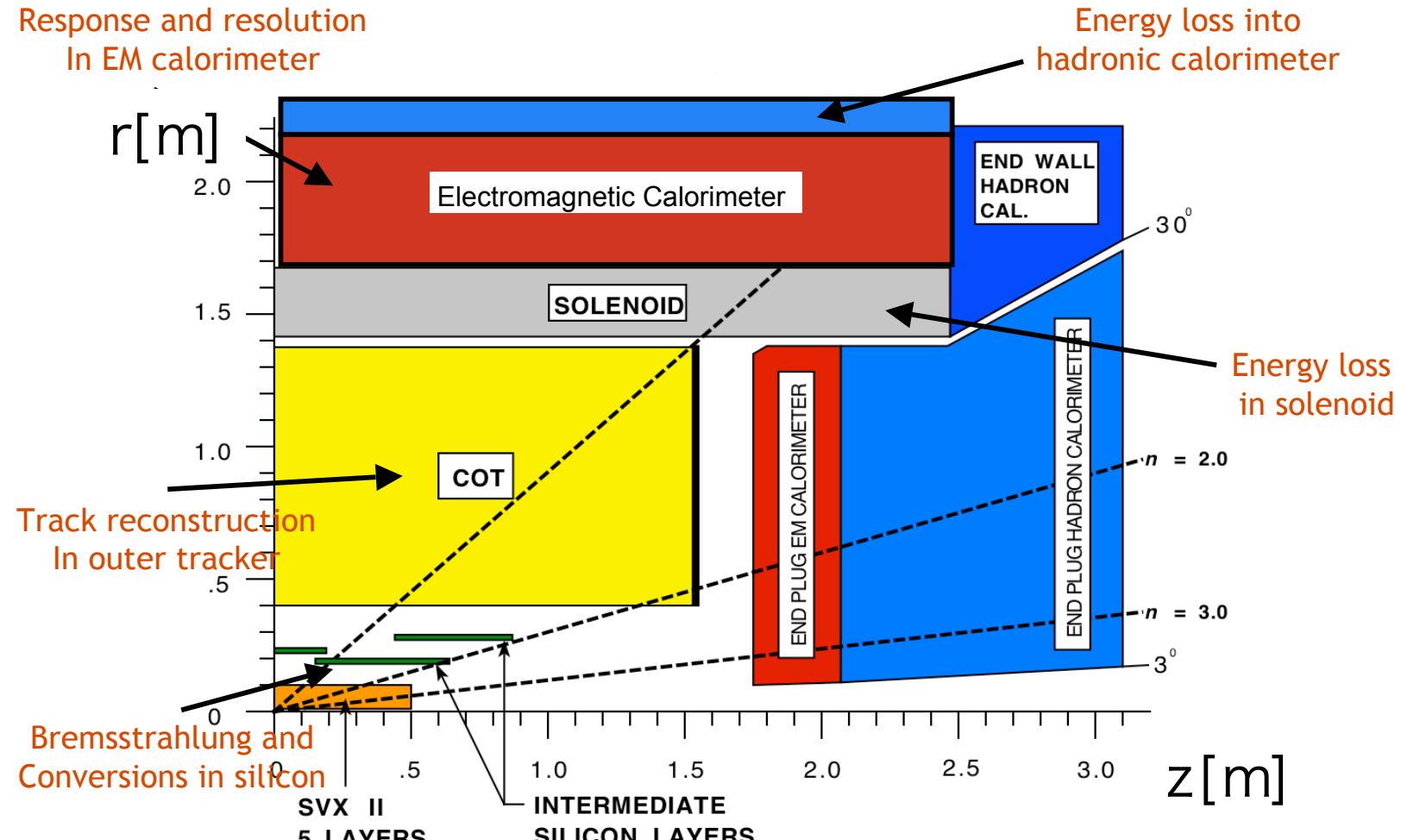
EM Calorimeter Scale Calibration

Calorimeter Energy Calibration

- Transfer momentum calibration to calorimeter by fitting peak of E/p distribution of electrons from W decay
- Additional physics effects beyond those for muon tracks
 - photon radiation and conversion

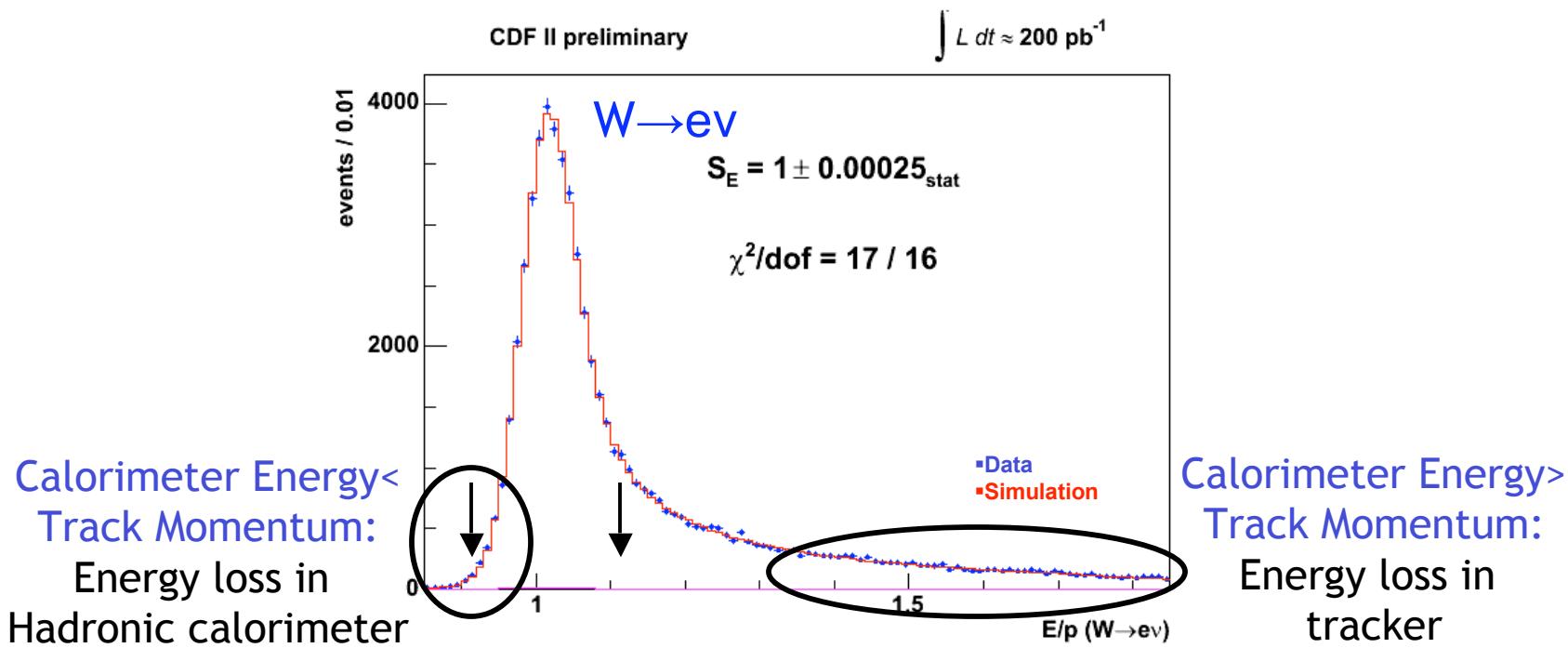


Full Electron Simulation

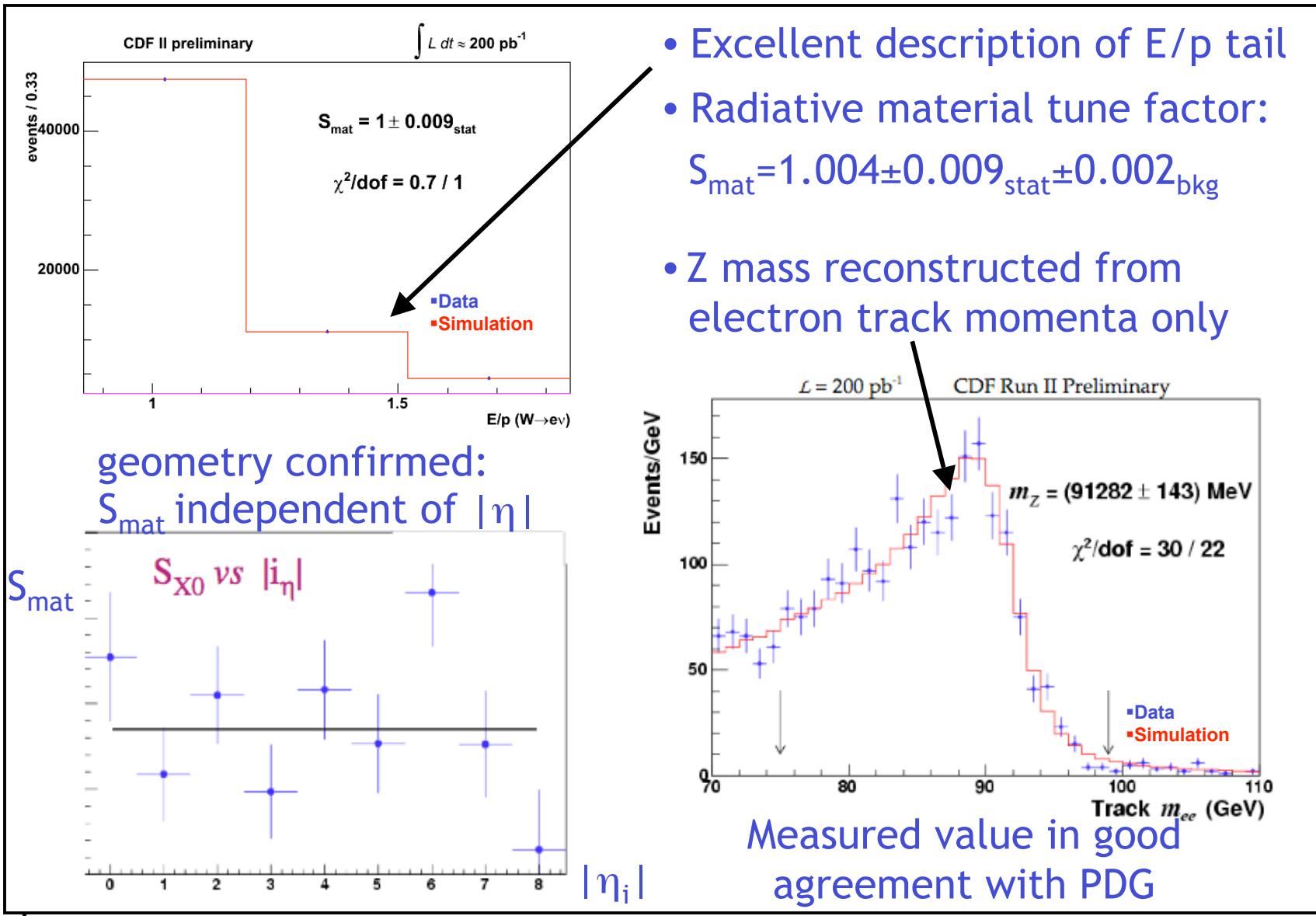


Energy Scale Calibration

- Calibrate calorimeter energy with peak of E/p distribution
- Energy Scale S_E set to $S_E = 1 \pm 0.00025_{\text{stat}} \pm 0.00011_{\chi^2} \pm 0.00021_{\text{Tracker}}$
- Setting S_E to 1 using E/p calibration

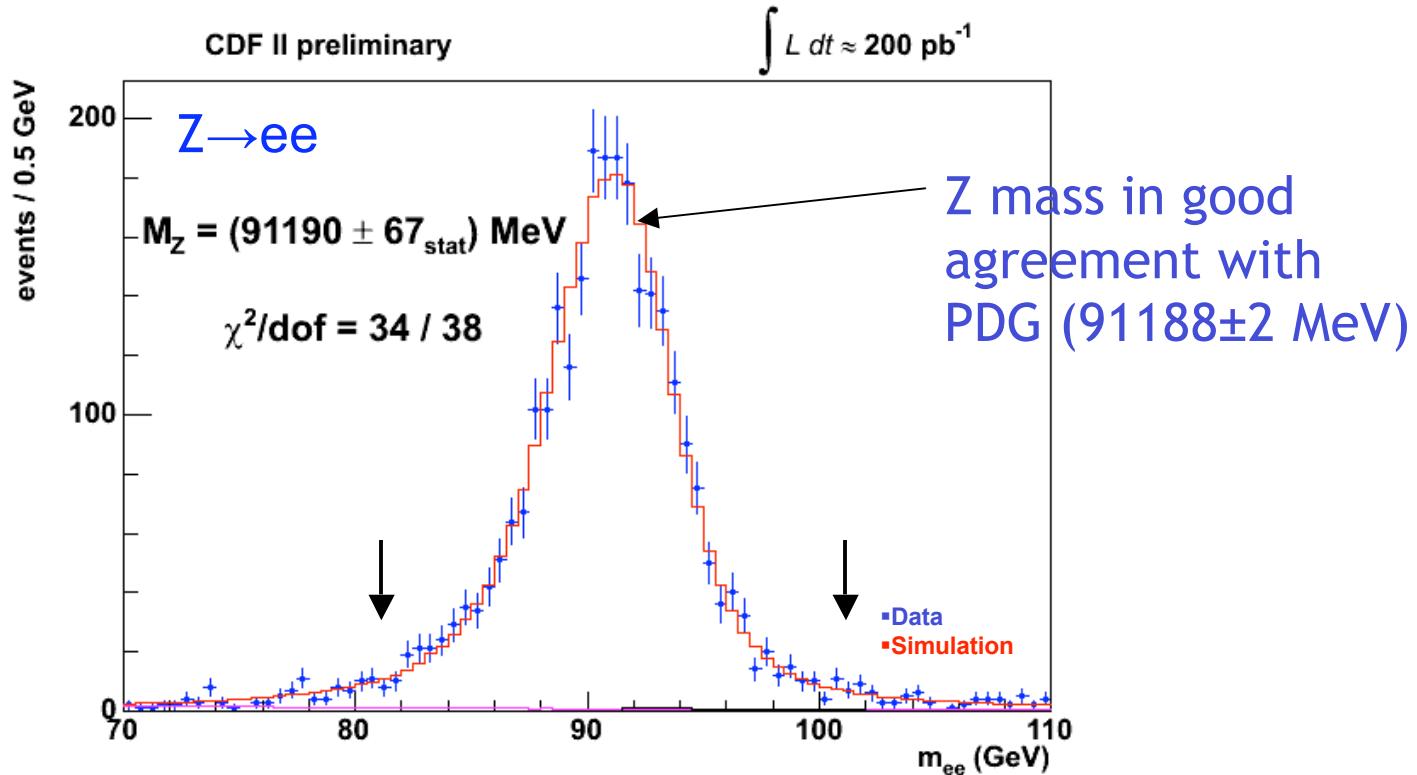


Consistency of Radiative Material Model



Z Mass Cross-Check and Final Energy Scale

- Fit Z Mass using scale from E/p calibration
- Measure non-linearity through E/p fits in bins of E_T in $W \rightarrow e\nu$ and $Z \rightarrow ee$ data and apply correction to simulation



- Include $Z \rightarrow ee$ mass for final energy scale (30% weight)
 $\Delta M_W = 30 \text{ MeV}$

Detector Resolutions

- Tracking resolution parametrized in fast Monte Carlo by
 - Drift chamber hit resolution $\sigma_h = 150 \pm 3_{\text{stat}} \mu\text{m}$
 - Beamspot size $\sigma_b = 39 \pm 3_{\text{stat}} \mu\text{m}$
 - Tuned on widths of $Z \rightarrow \mu\mu$ and $Y \rightarrow \mu\mu$ distribution

$$\Delta M_W = 3 \text{ MeV}$$

- Electron cluster resolution parametrized by $13.5\%/\sqrt{E_T} + \kappa$
 - primary electron constant term: $\kappa = 0.89 \pm 0.15_{\text{stat}} \%$
 - secondary photon resolution: $\kappa = 8.3 \pm 2.2_{\text{stat}} \%$
- Tuned on the widths of the E/p peak and $Z \rightarrow ee$ peak (selecting radiative electrons)

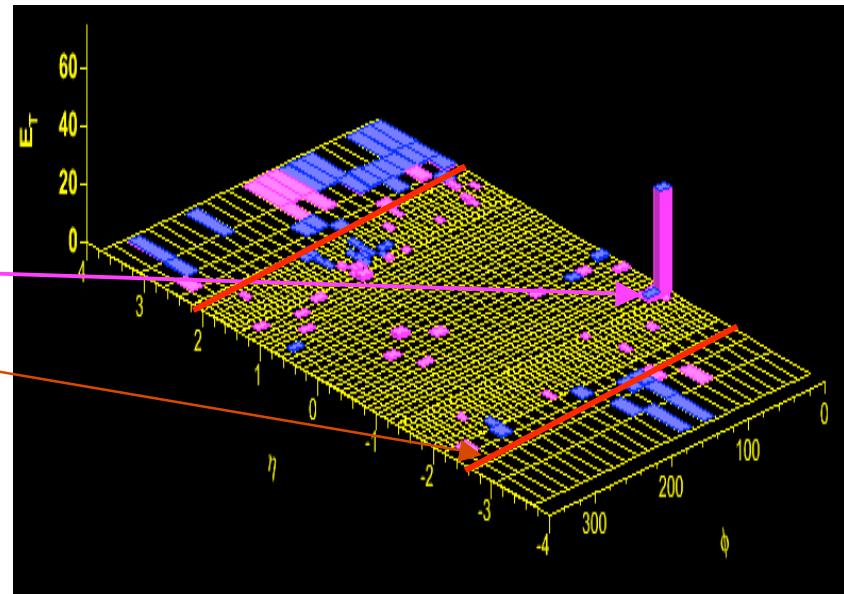
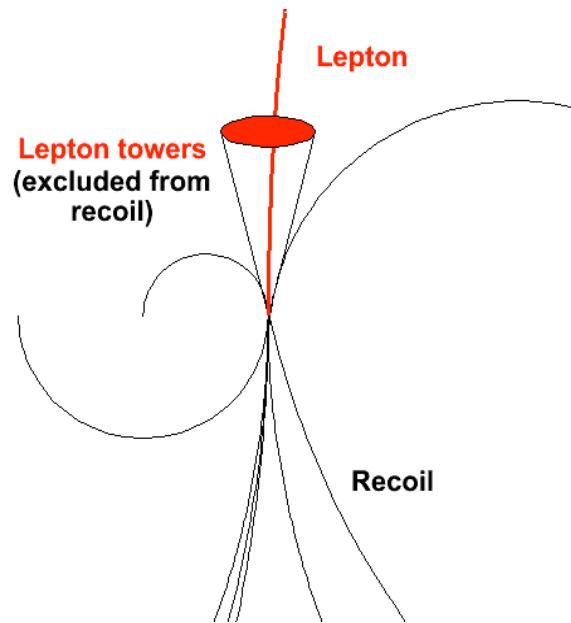
$$\Delta M_W = 9 \text{ MeV}$$

Hadronic Recoil Model

Hadronic Recoil Definition

Recoil definition:

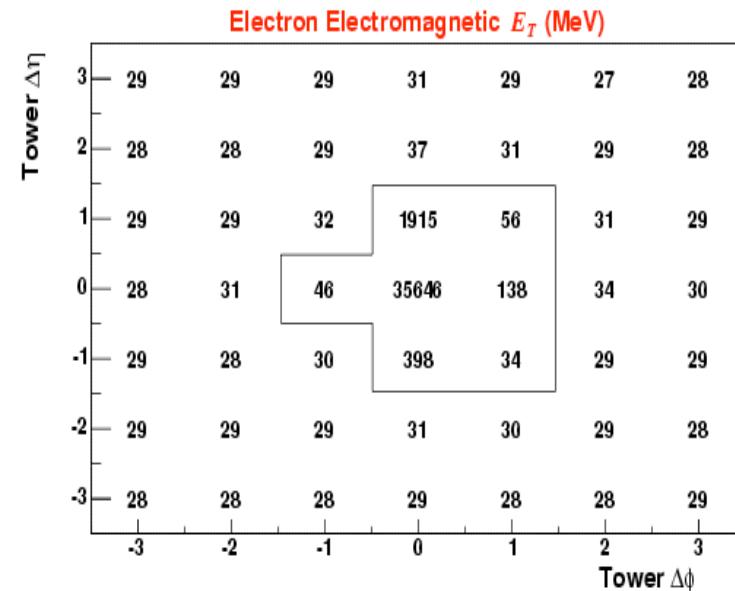
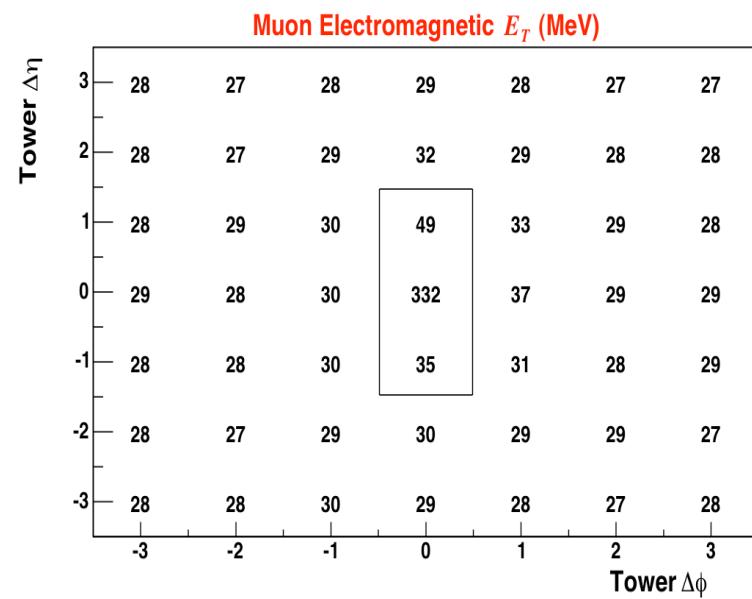
- Energy vector sum over all calorimeter towers, excluding:
 - lepton towers
 - towers near beamline (“ring of fire”)



- Lepton removal also removes underlying event
→ Need to measure recoil under lepton
- Recoil under lepton depends on lepton tower definition

Lepton Removal

- Estimate removed recoil energy using towers separated in Φ
- Model tower removal in simulation



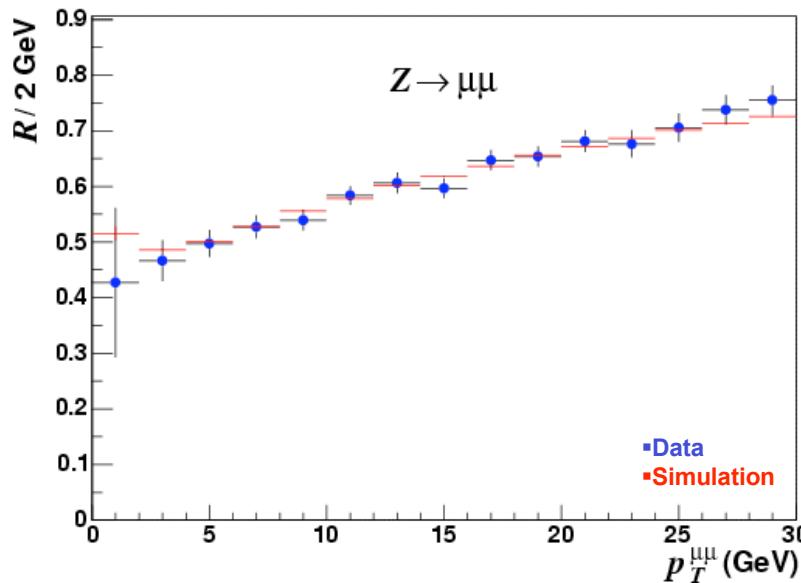
Muons: Remove 3 towers (MIP)
 $\Delta M_W = 5 \text{ MeV}$

Electrons: Remove 7 towers
keystone (shower)
 $\Delta M_W = 8 \text{ MeV}$

Hadronic Recoil Simulation

Recoil momentum vector u has two components:

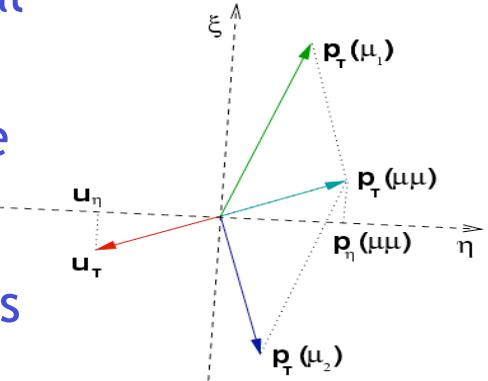
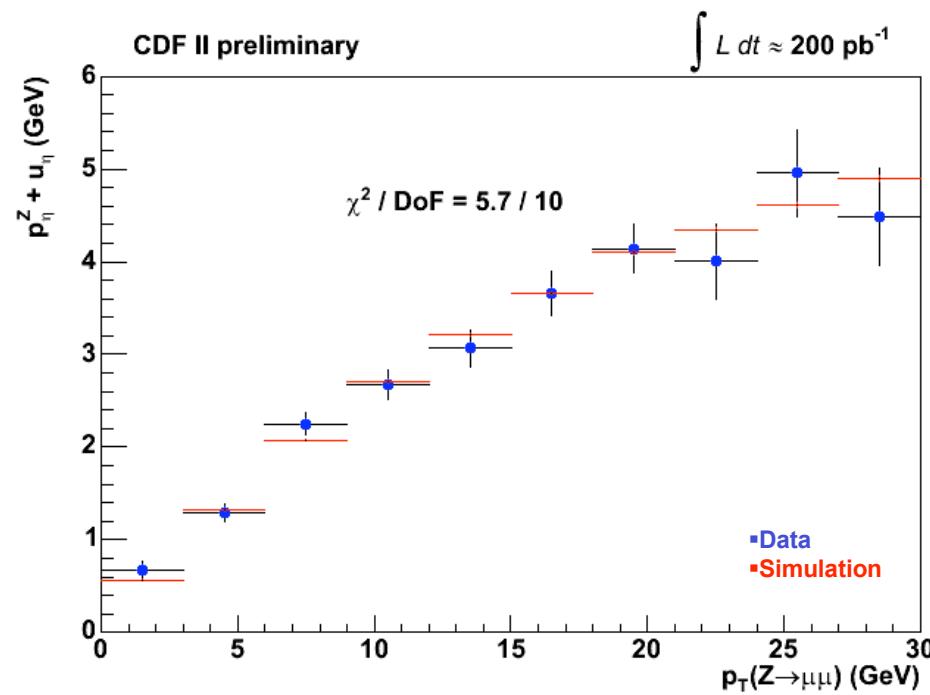
- Soft spectator interaction component, randomly oriented
 - modelled using minimum bias data with tuneable magnitude
- A hard ‘jet’ component, directed opposite the boson p_T
 - p_T -dependent response and resolution parametrization
 - Hadronic response $R = (u_{\text{meas}} / u_{\text{true}})$
 - R parametrized as a logarithmically increasing function of boson p_T



motivated by
Z boson data

Hadronic Recoil Response Calibration

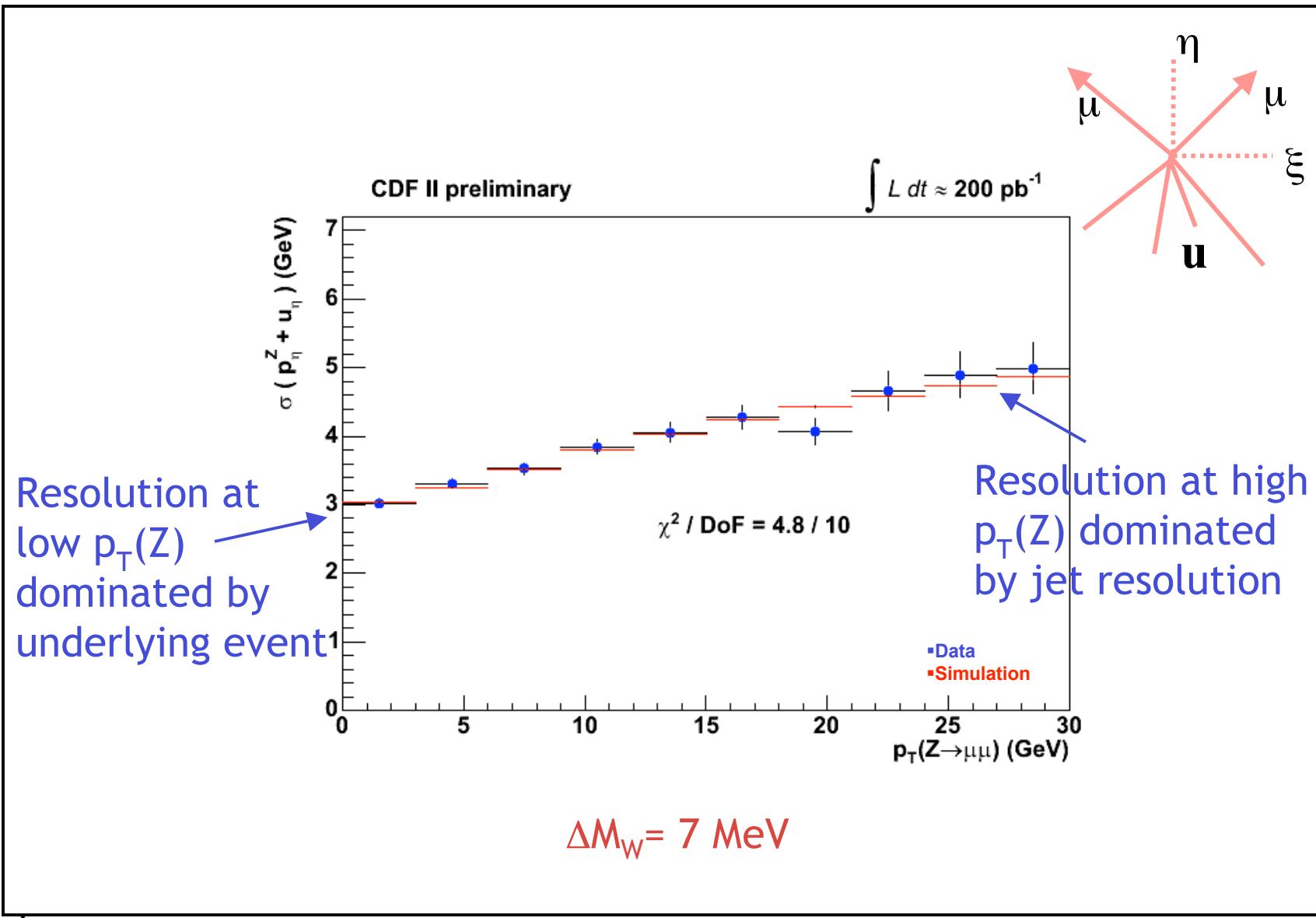
- Project vector sum of $p_T(l\bar{l})$ and u on orthogonal axes defined by lepton directions
- Use Z balancing to calibrate recoil energy scale
- Mean and RMS of projections as a function of $p_T(l\bar{l})$ provide information for model parameters



Hadronic model parameters tuned by minimizing χ^2 between data and simulation

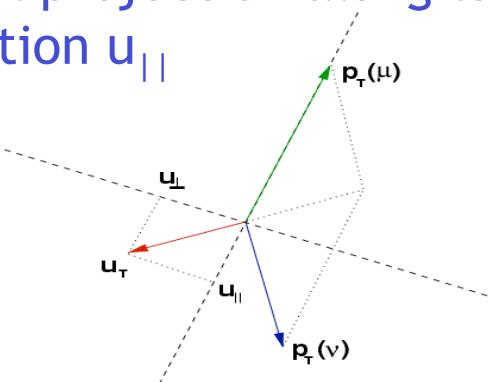
$$\Delta M_W = 9 \text{ MeV}$$

Hadronic Recoil Resolution Calibration



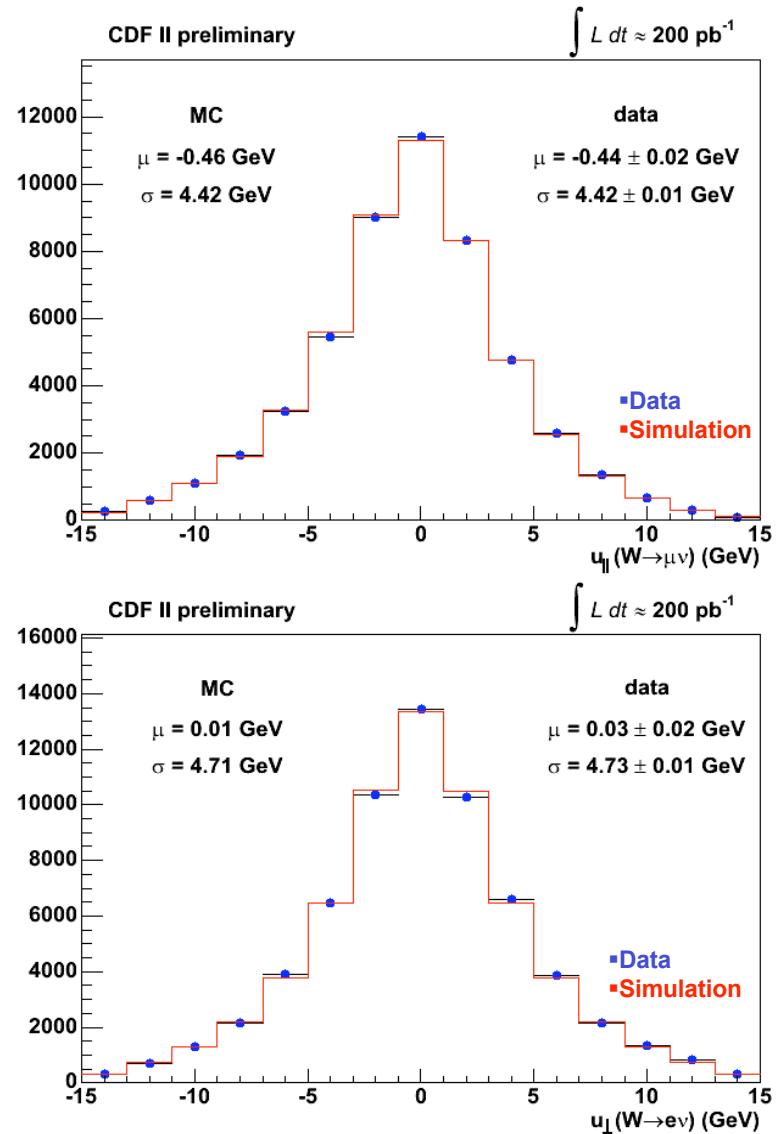
Recoil Model Checks

- Apply model to W sample to check recoil model from Z's
- Recoil projection along lepton direction $u_{||}$



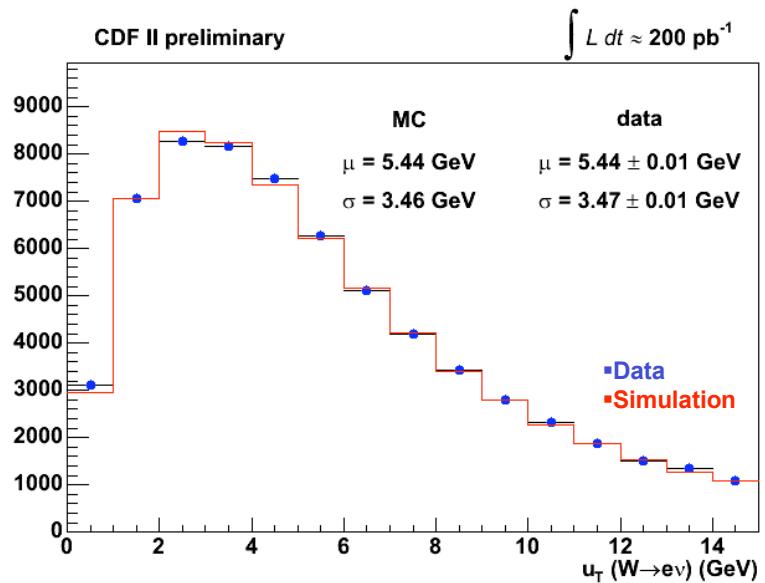
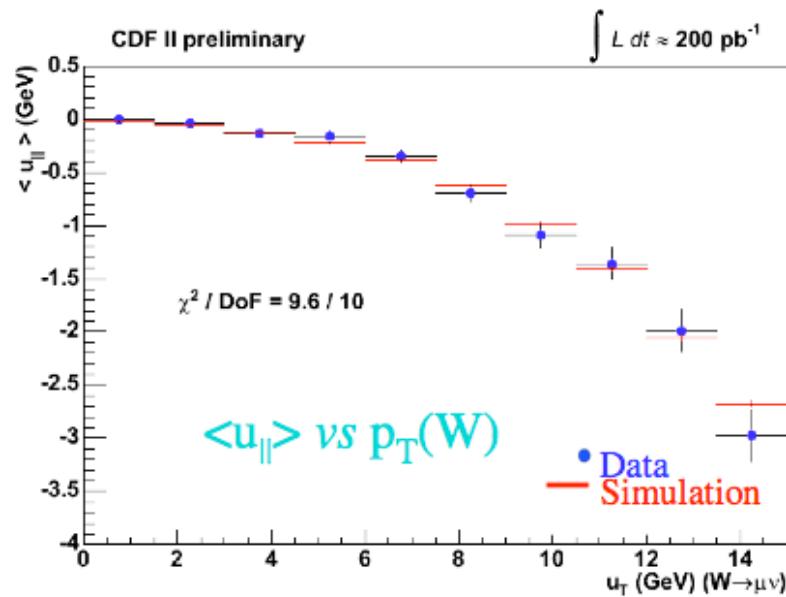
→ directly affects m_T fits
 → Sensitive to: lepton removal, efficiency model, scale, resolution, W decay

- Recoil projection perpendicular to lepton direction u_{\perp}
 → Sensitive to resolution model



Recoil Model Checks

- Recoil distribution
 - Sensitive to recoil scale, resolution and boson p_T

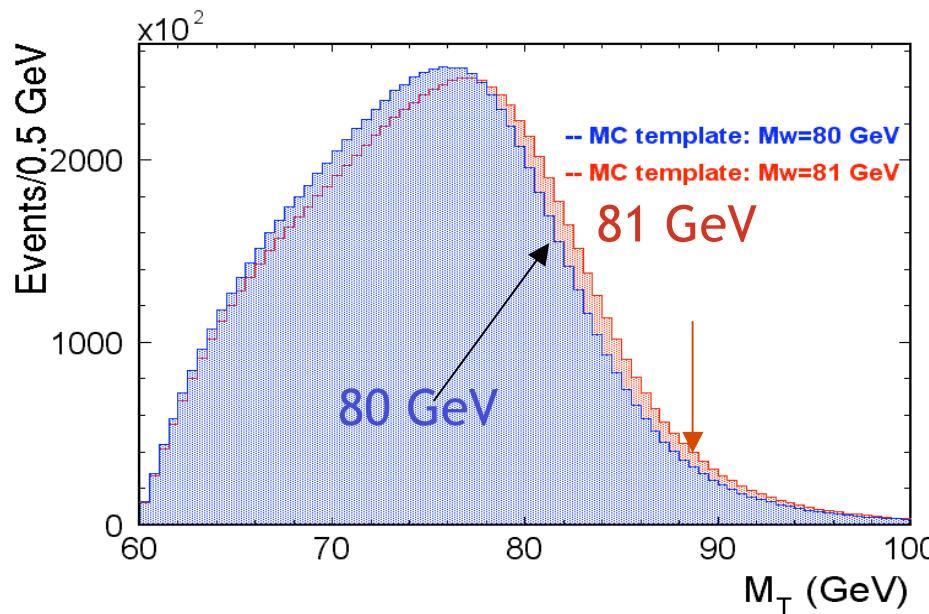


- Recoil model validation plots confirm the consistency of the model

Event Simulation

Signal Simulation and Template Fitting

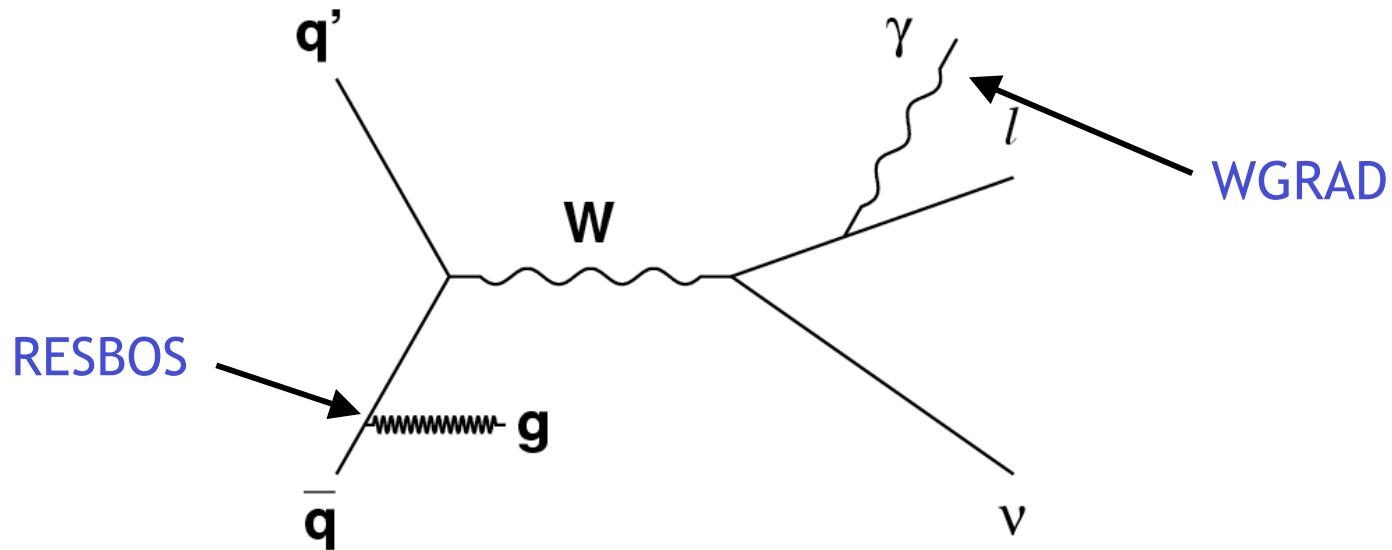
- All signals simulated using a fast simulation
 - Generate finely-spaced templates as a function of fit variable
 - perform binned maximum-likelihood fits to the data
- Custom fast simulation makes smooth, high statistics templates
 - provides analysis control over key components of simulation



- We will extract the W mass from six kinematic distributions:
 m_T , p_T and ξ_T for muon and electron channel

Generator-level Signal Simulation

- Generator-level input for W&Z simulation provided by RESBOS [Balazs *et.al.* PRD56, 5558 (1997)]

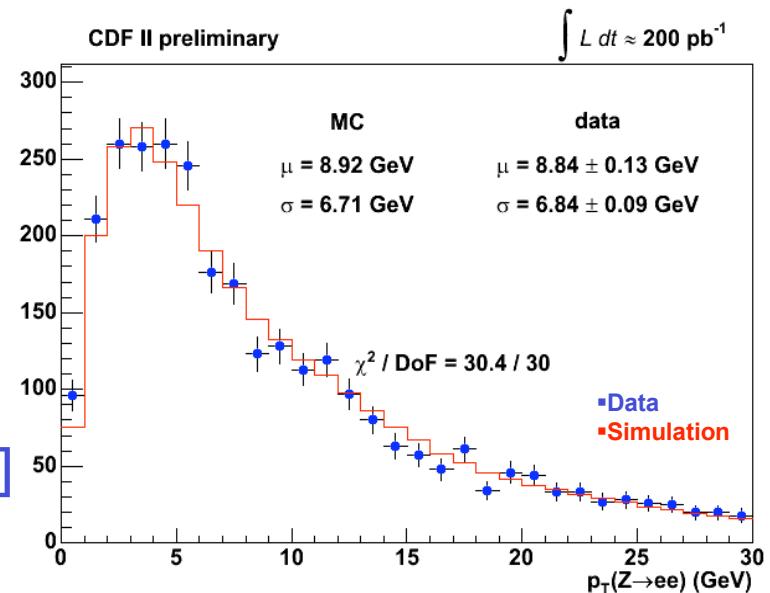
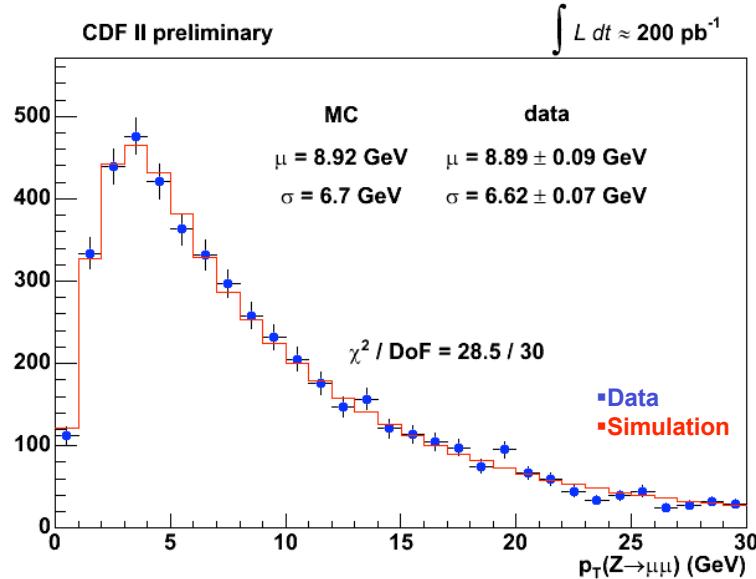


- Radiative photons generated according to energy vs angle lookup table from WGRAD [Baur *et.al.* PRD59, 013002 (1998)]
 - Simulate FSR (ISR, photons off the propagator, $\Delta M_W < 5$ MeV)
 - Apply 10% correction for 2nd photon [Calame *et.al.* PRD69, 037301 (2004)] and take 5% systematic uncertainty
- $\Delta M_W = 11 \text{ (12) MeV for } e \text{ (}\mu\text{)}$

Boson p_T Model

- Model boson p_T using RESBOS generator
- non perturbative regime at low p_T parametrized with g_1 , g_2 , g_3 parameters

[Landry *et.al.* PRD67, 073016 (2003)]



- g_2 parameter determines position of peak in p_T distribution
- Measure g_2 with Z boson data (other parameters negligible)
- Find: $g_2 = 0.685 \pm 0.048$

$$\Delta M_W = 3 \text{ MeV}$$

Parton Distribution Functions

- Affect W kinematic lineshape through acceptance cuts
(only use $|\eta| < 1$)
- We use CTEQ6M as the default
- Use CTEQ6 ensemble of 20 ‘uncertainty PDFs’:
[Pumplin *et.al.* JHEP, 0207 (2002)]
 - 20 free parameters in global fit
 - compute ΔM_W contribution from each error PDF
- Using CTEQ prescription and interpreting ensemble as 90% CL

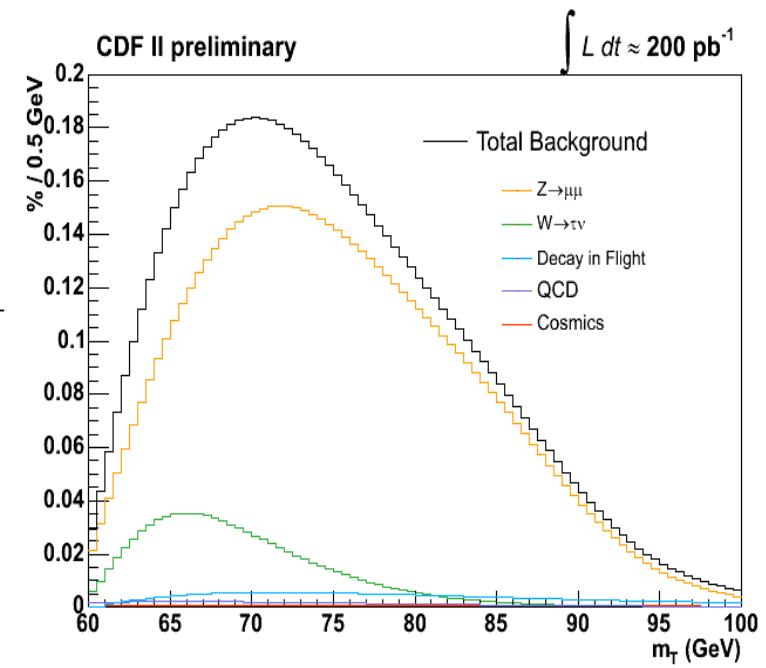
$$\Delta M_W = 11 \text{ MeV}$$

- Cross-check: Fitting MC sample generated with MRST2003
[Martin *et.al.* Eur. Phys. Jour. C28, 455 (2003)] with default
CTEQ6M template yields a 8 MeV shift in W mass

Backgrounds

- Backgrounds have very different lineshapes compared to W signal
 - distributions are added to template
 - QCD measured with data
 - EWK predicted with Monte Carlo

Background	% (Muons)	% (Electrons)
Hadronic Jets	0.1 ± 0.1	0.25 ± 0.15
Decay in Flight	0.3 ± 0.2	-
Cosmic Rays	0.05 ± 0.05	-
$Z \rightarrow \mu\mu$	6.6 ± 0.3	0.24 ± 0.04
$W \rightarrow \tau\nu$	0.89 ± 0.02	0.93 ± 0.03



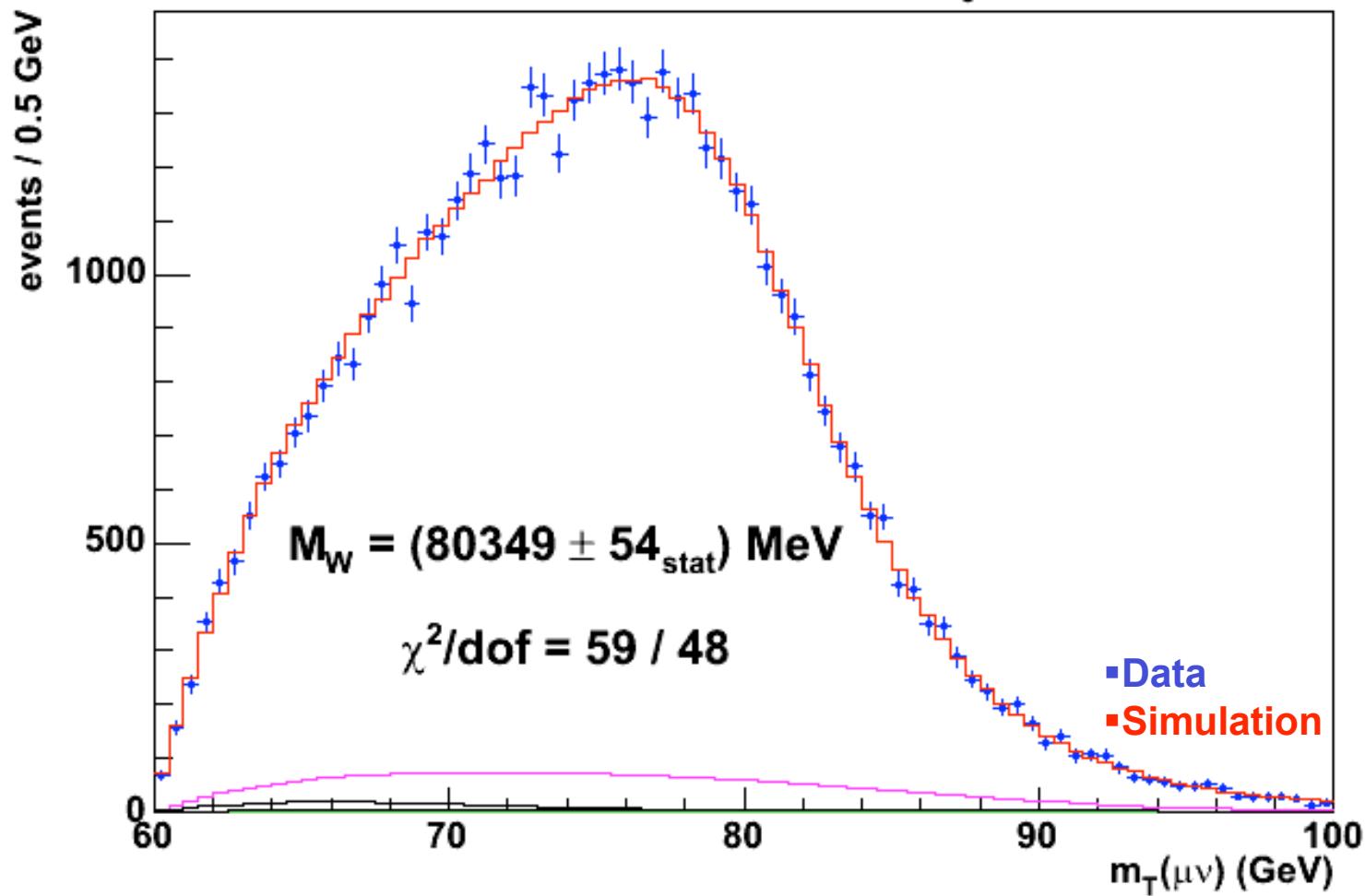
$$\Delta M_W = 8 \text{ (9) MeV for } e \text{ (\mu)}$$

W Boson Mass Fits

Transverse Mass Fit (Muons)

CDF II preliminary

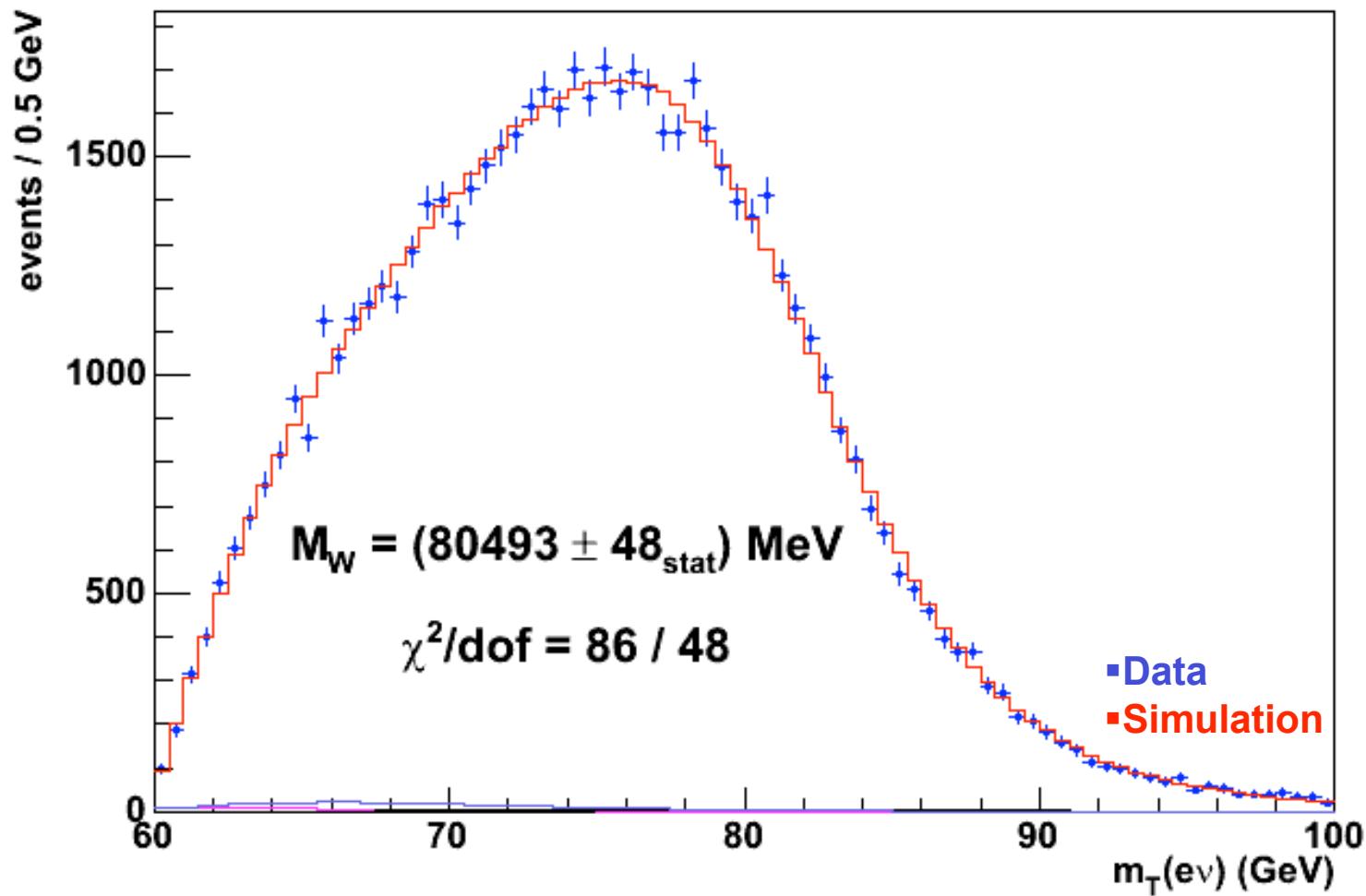
$\int L dt \approx 200 \text{ pb}^{-1}$



Transverse Mass Fit (Electrons)

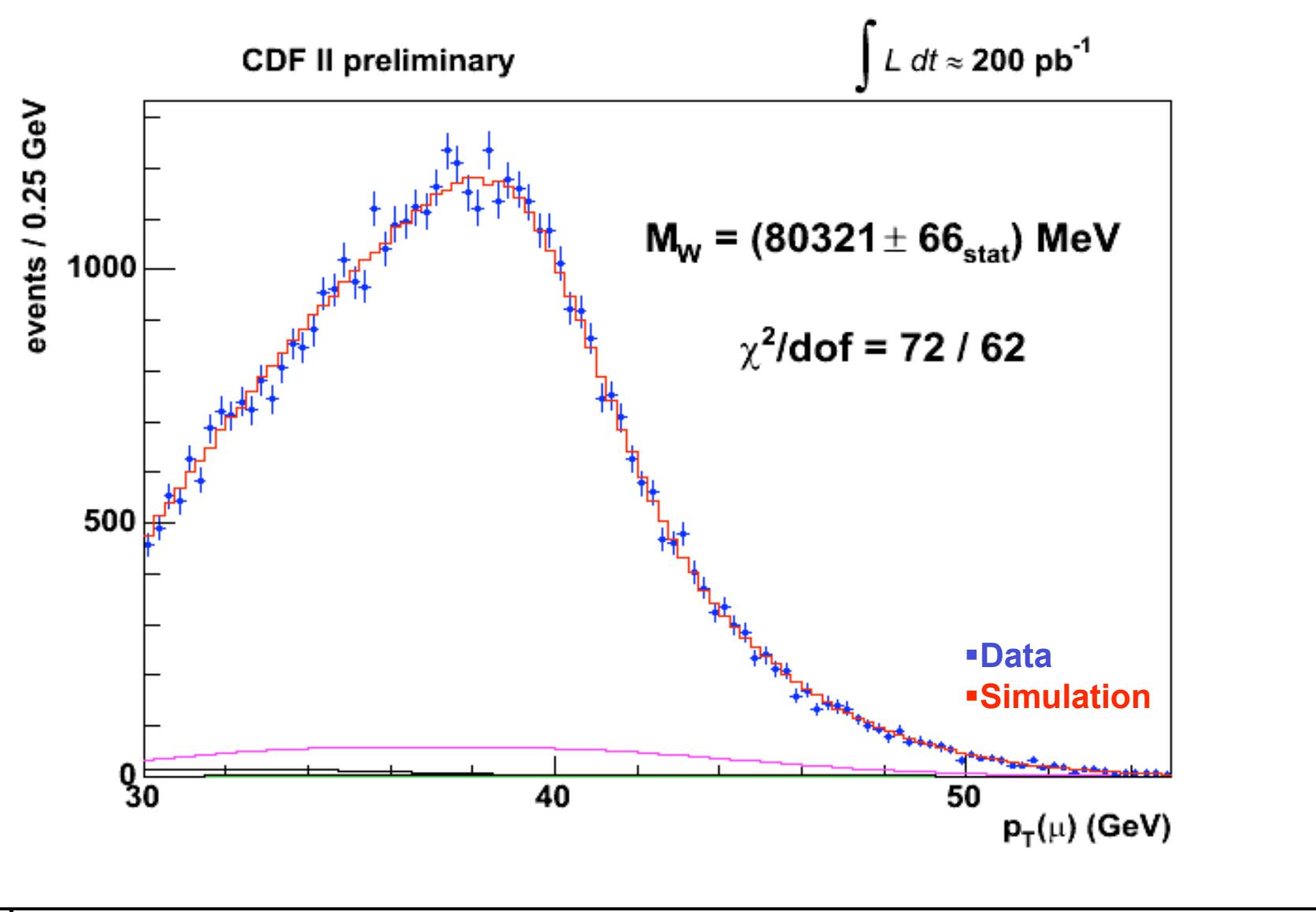
CDF II preliminary

$\int L dt \approx 200 \text{ pb}^{-1}$

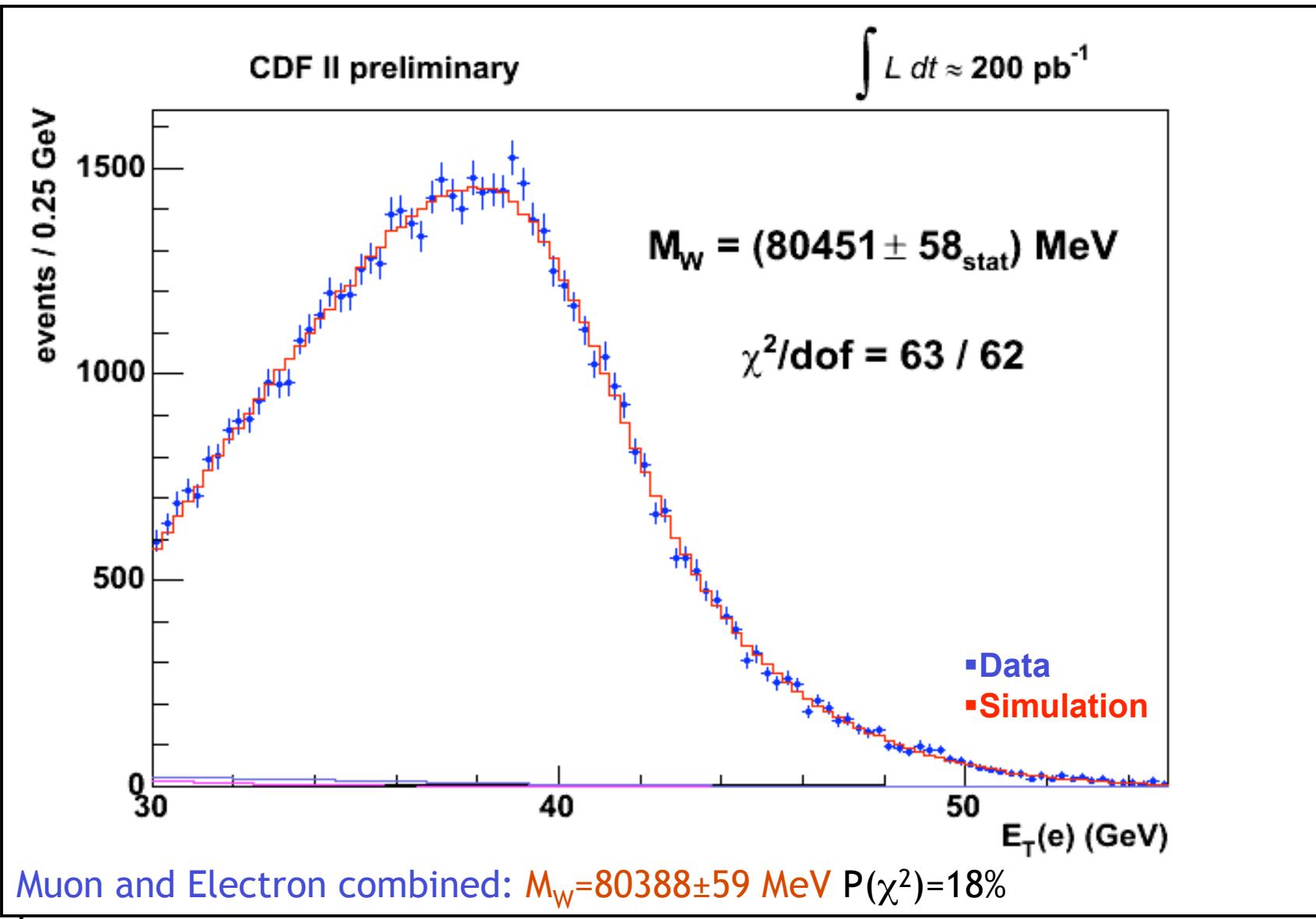


Muon and Electron combined: $M_W=80417\pm48 \text{ MeV}$ $P(\chi^2)=7\%$

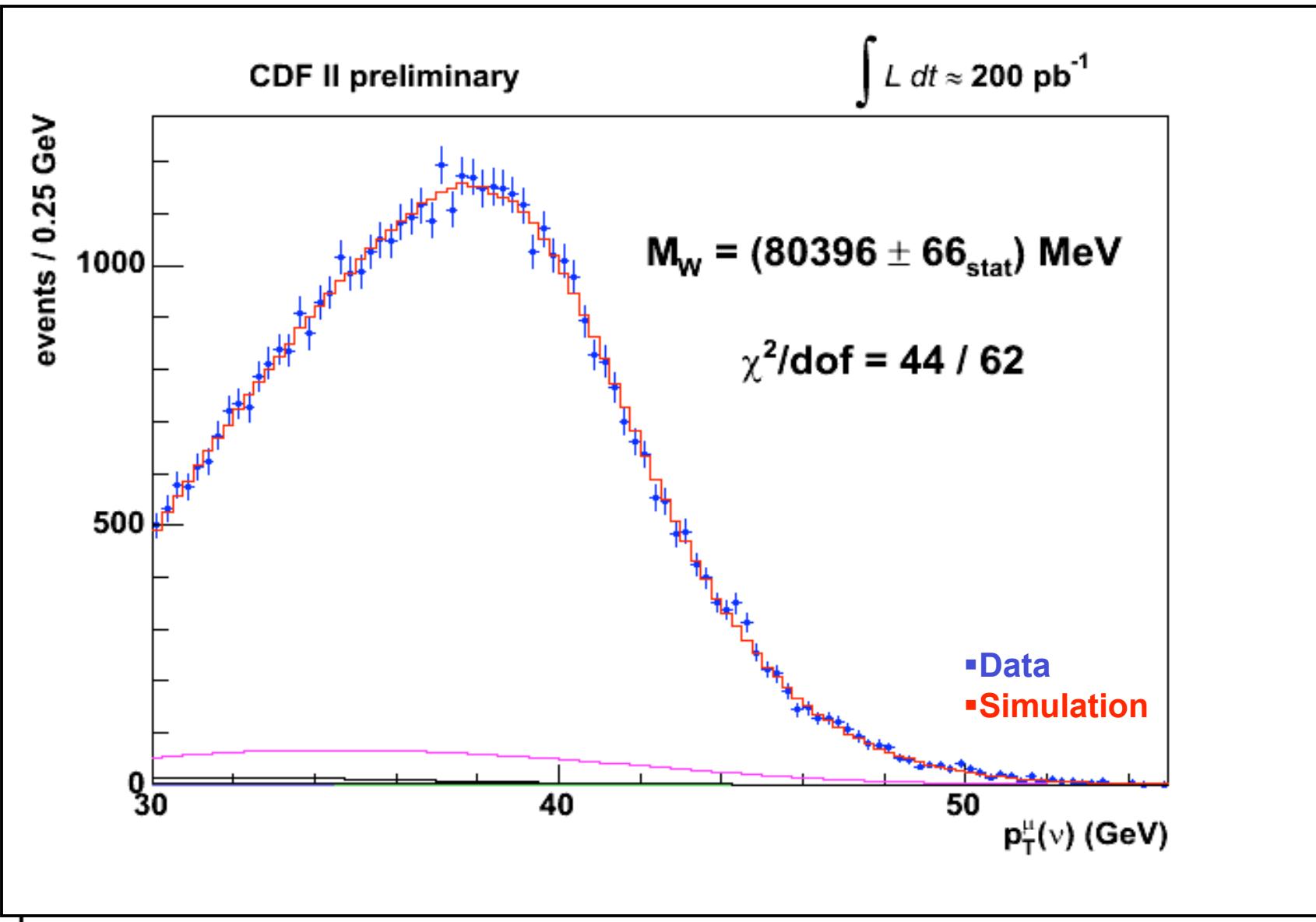
Transverse Momentum Fit (Muons)



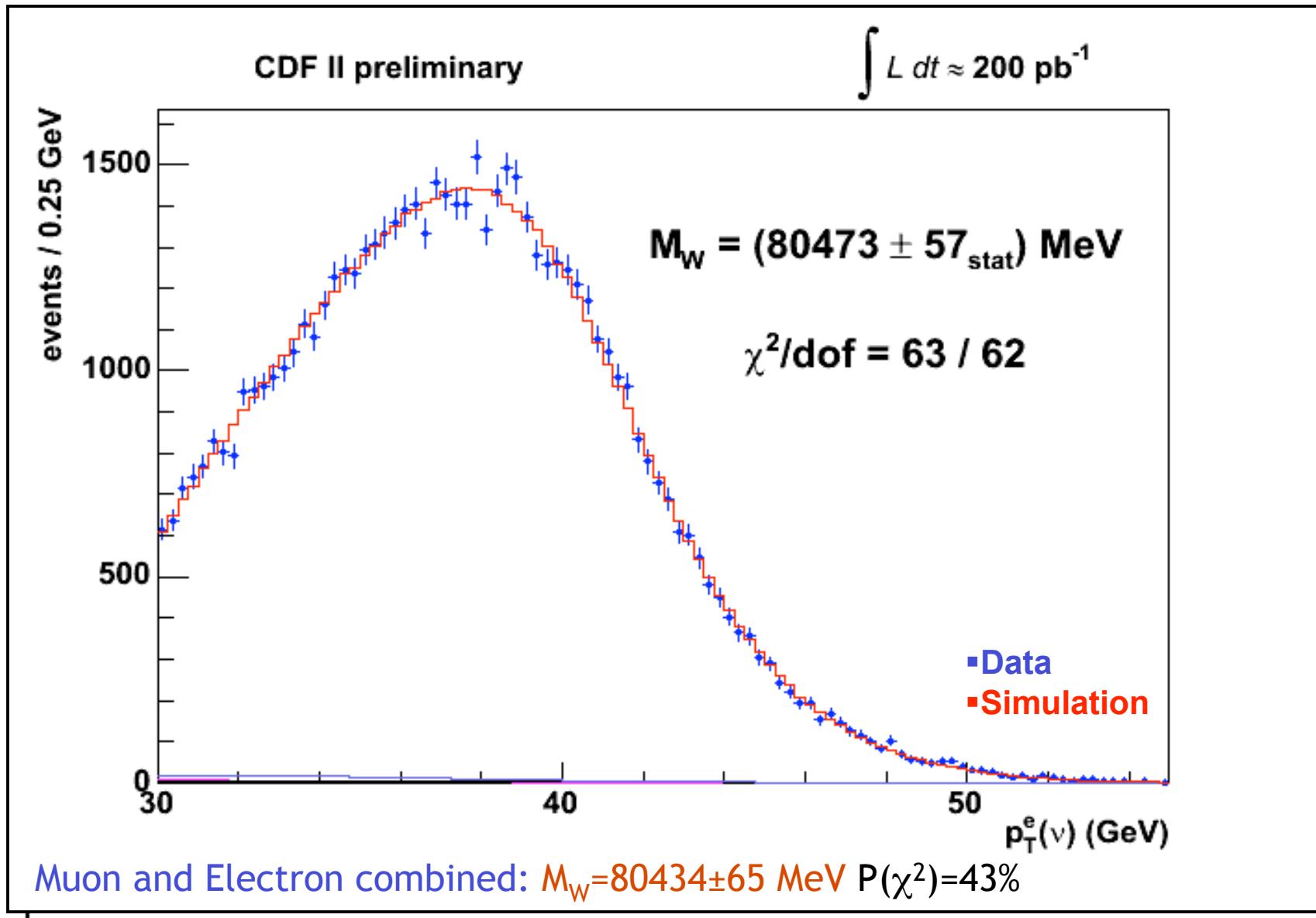
Transverse Energy Fit (Electrons)



Missing Transverse Energy Fit (Muons)



Missing Transverse Energy Fit (Electrons)



Systematic Uncertainty

Systematic uncertainty on transverse mass fit

CDF II preliminary

$L = 200 \text{ pb}^{-1}$

m_T Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
$u_{ }$ Efficiency	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
$p_T(W)$	3	3	3
PDF	11	11	11
QED	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total	62	60	26

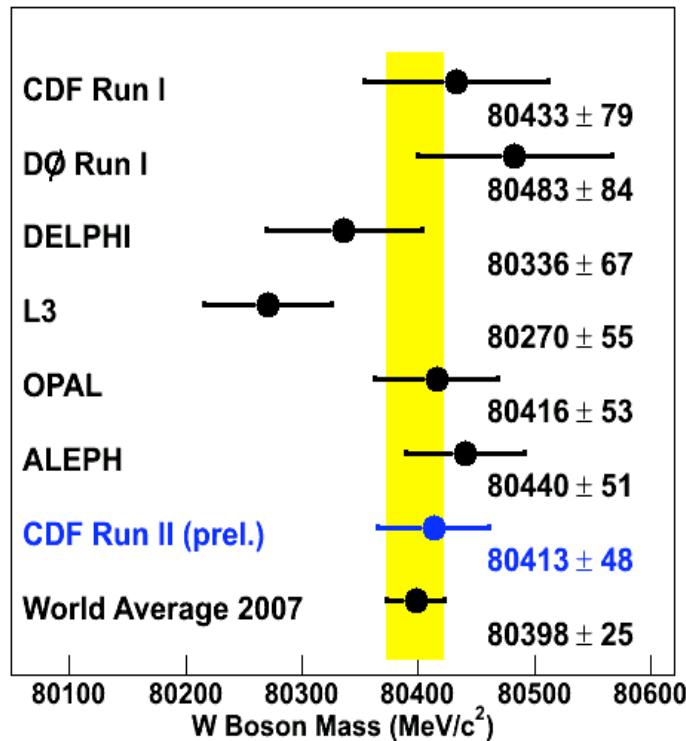
⇒ Combined Uncertainty: 48 MeV for 200 pb⁻¹

Results

- Combining all six mass fits yields:

$$M_W = 80413 \pm 48 \text{ MeV (stat+syst)}, P(\chi^2) = 44\%$$

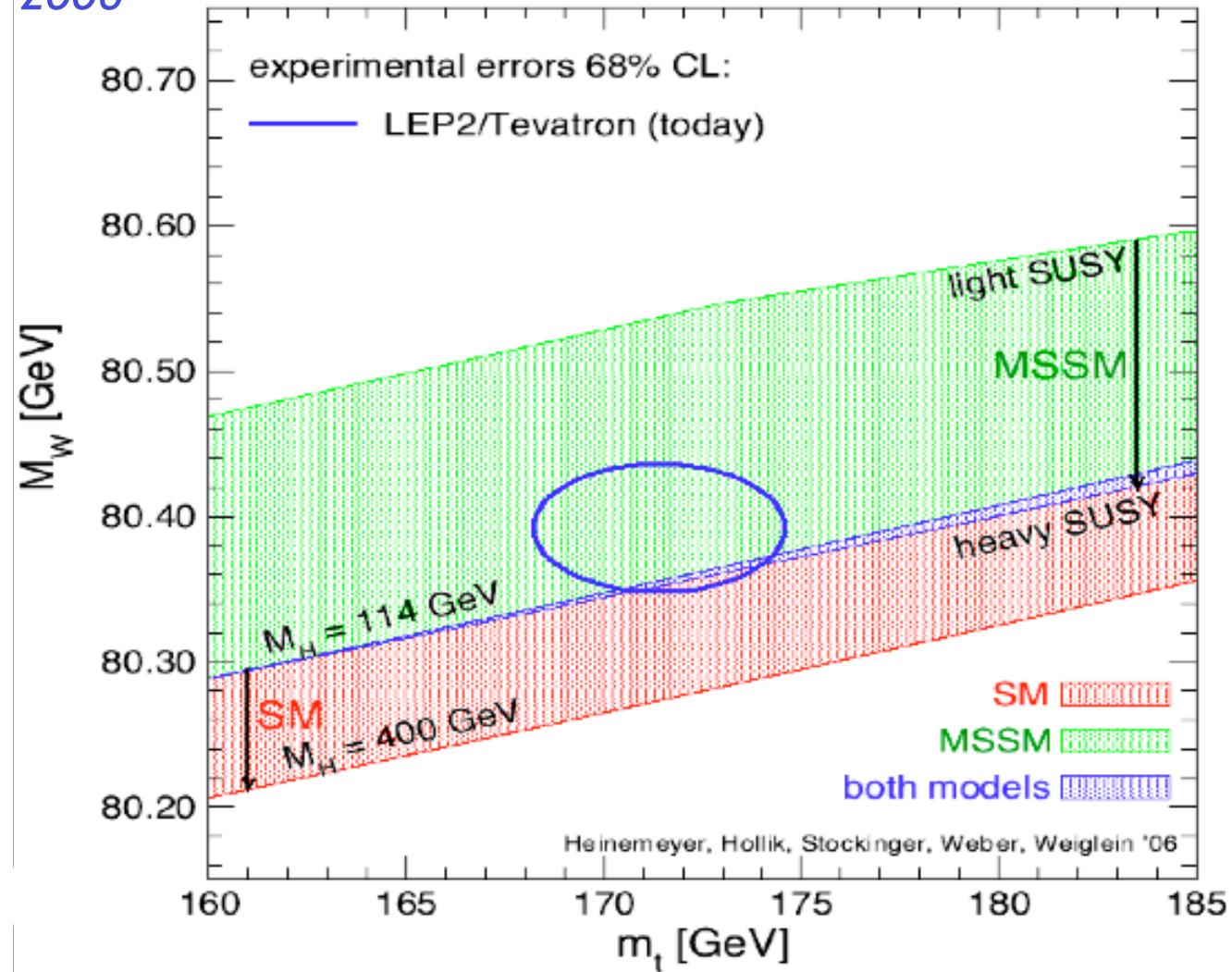
- New CDF result is the world's most precise single measurement



- World average increases:
80392 to 80398 MeV
- Uncertainty reduced ~15%
(29 to 25 MeV)

Previous M_W vs M_{top}

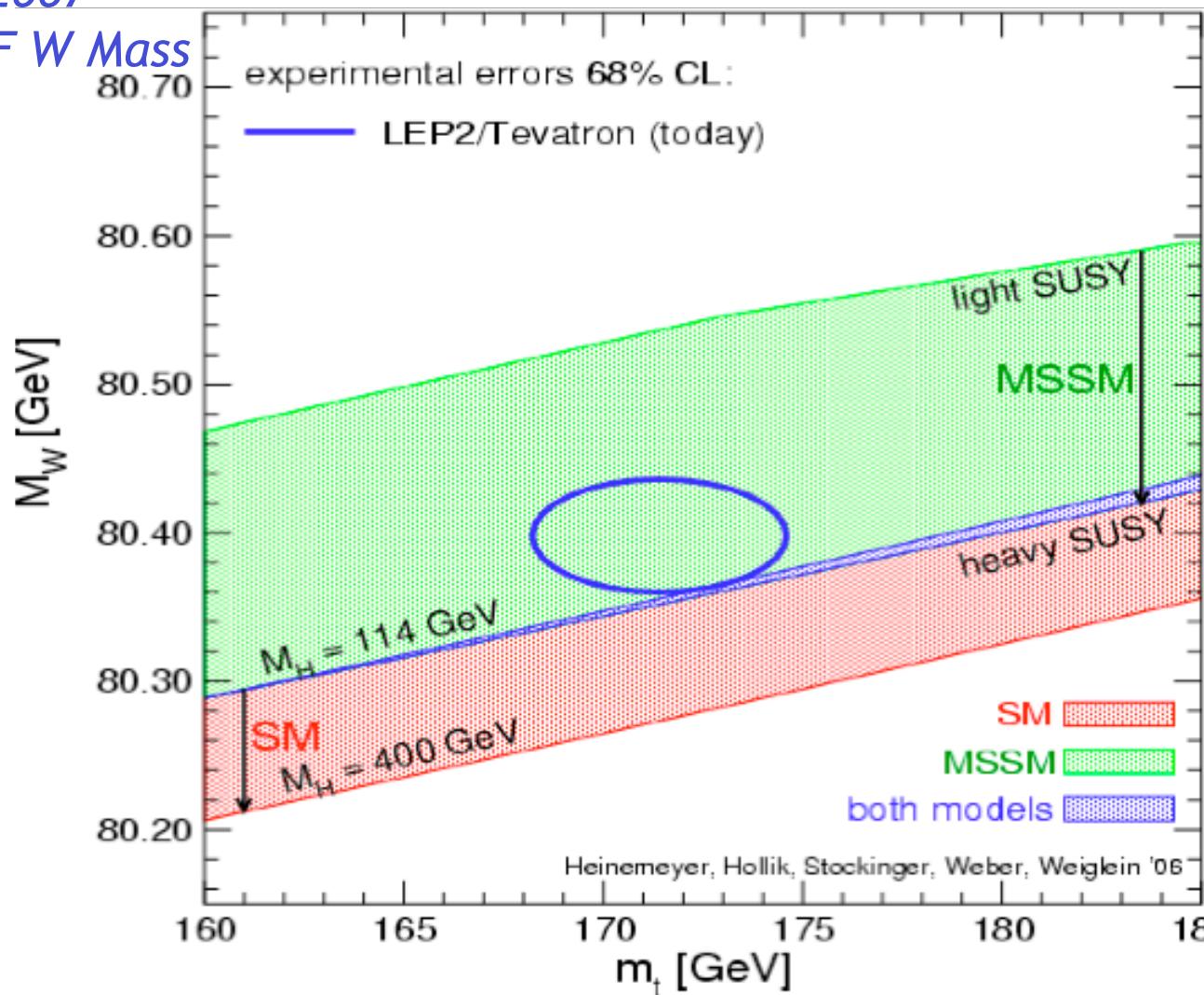
Summer 2006



Updated M_W vs M_{top}

Winter 2007

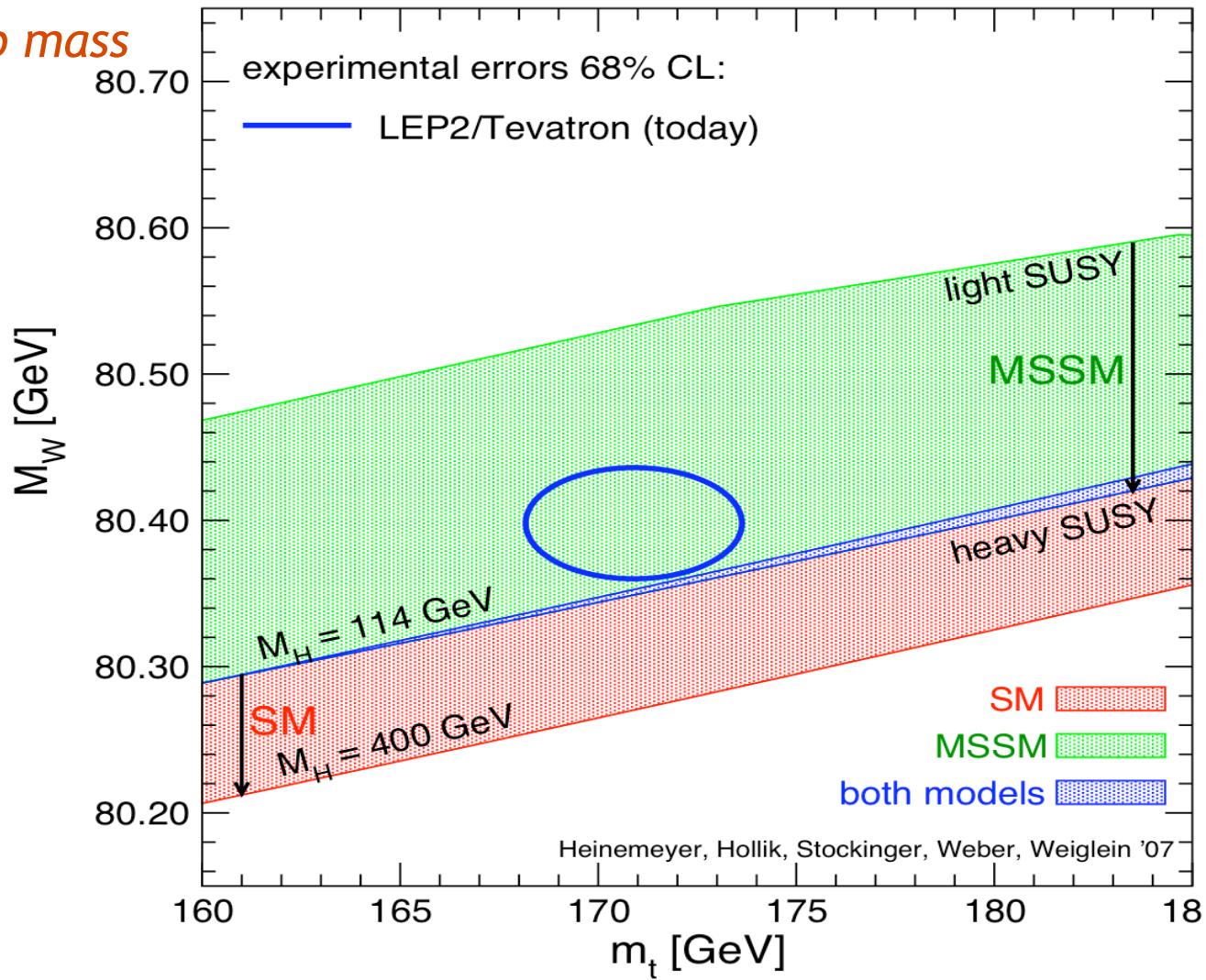
New CDF W Mass



Latest Higgs Constraint

March 2007

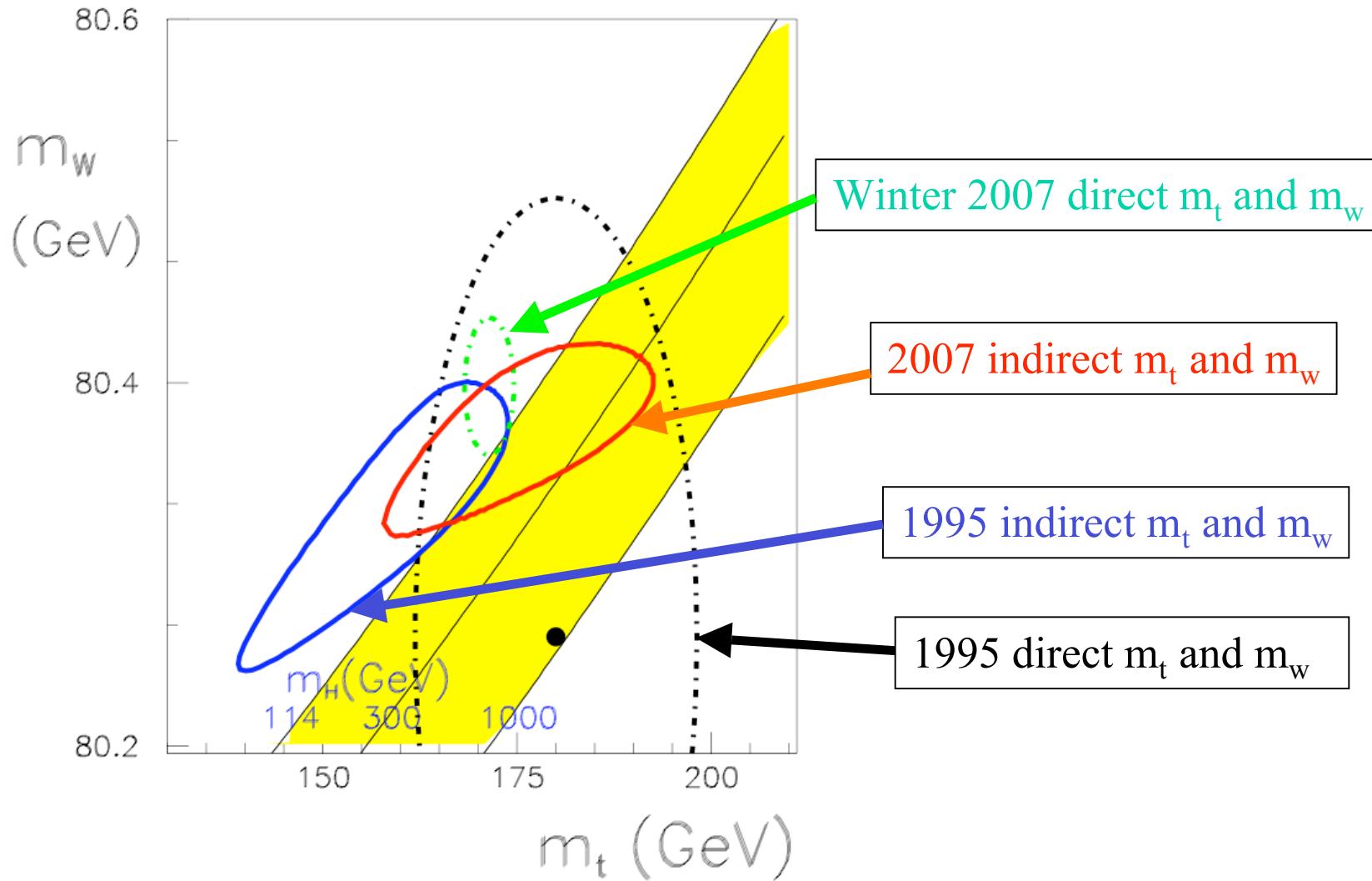
New top mass



Standard Model Higgs Constraint

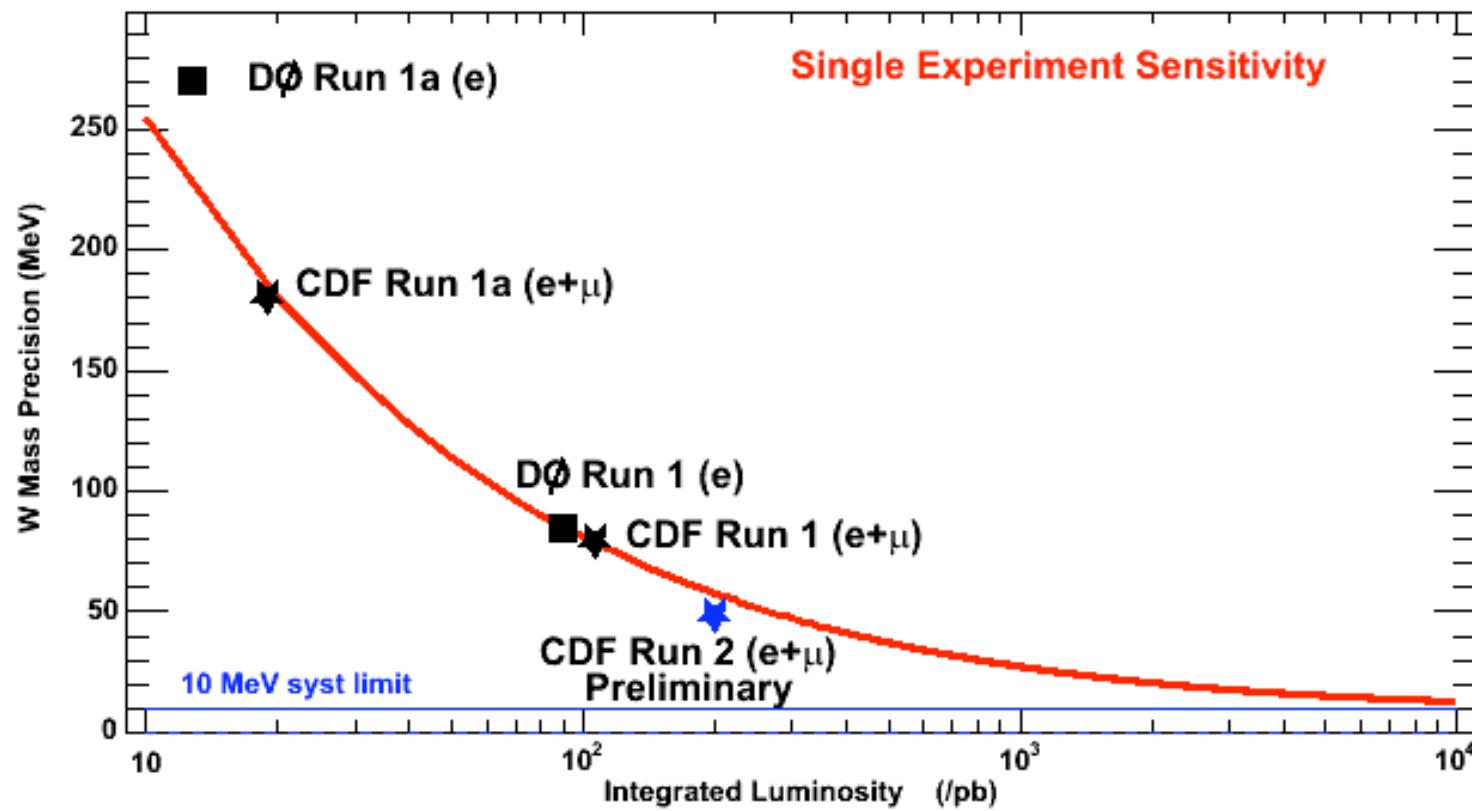
- Summer 2006 SM Higgs fit: (LEP EWWG)
 - $M_H = 85^{+39}_{-28}$ GeV
 - $M_H < 166$ GeV (95% CL)
 - $M_H < 199$ GeV (95% CL) Including LEPII direct exclusion
- Updated preliminary SM Higgs fit: (With new CDF W Mass)
 - $M_H = 80^{+36}_{-26}$ GeV (M. Grünwald, private communication)
 - $M_H < 153$ GeV (95% CL)
 - $M_H < 189$ GeV (95% CL) Including LEPII direct exclusion
- Updated preliminary SM Higgs fit: (With new Tevatron top mass)
 - $M_H = 76^{+33}_{-24}$ GeV
 - $M_H < 144$ GeV (95% CL)
 - $M_H < 182$ GeV (95% CL) Including LEPII direct exclusion

Progress since 1995



Projection

- Projection from previous Tevatron measurements



Summary

- W boson mass remains a very interesting parameter to measure with increasing precision
- CDF Run II measurement is the most precise single measurement

$$\begin{aligned} M_W &= 80413 \pm 34 \pm 34 \text{ MeV} \\ &= 80413 \pm 48 \text{ MeV (preliminary)} \end{aligned}$$

- New preliminary Higgs constraint $M_H = 76^{+33}_{-24}$ GeV (LEP EWWG) (including new CDF W boson mass and new top quark mass average)
 - Mass has moved further into the directly excluded region

Looking forward:

→ Expect $\Delta M_W < 25$ MeV with $> 1.5 \text{ fb}^{-1}$ already collected by CDF

Higgs

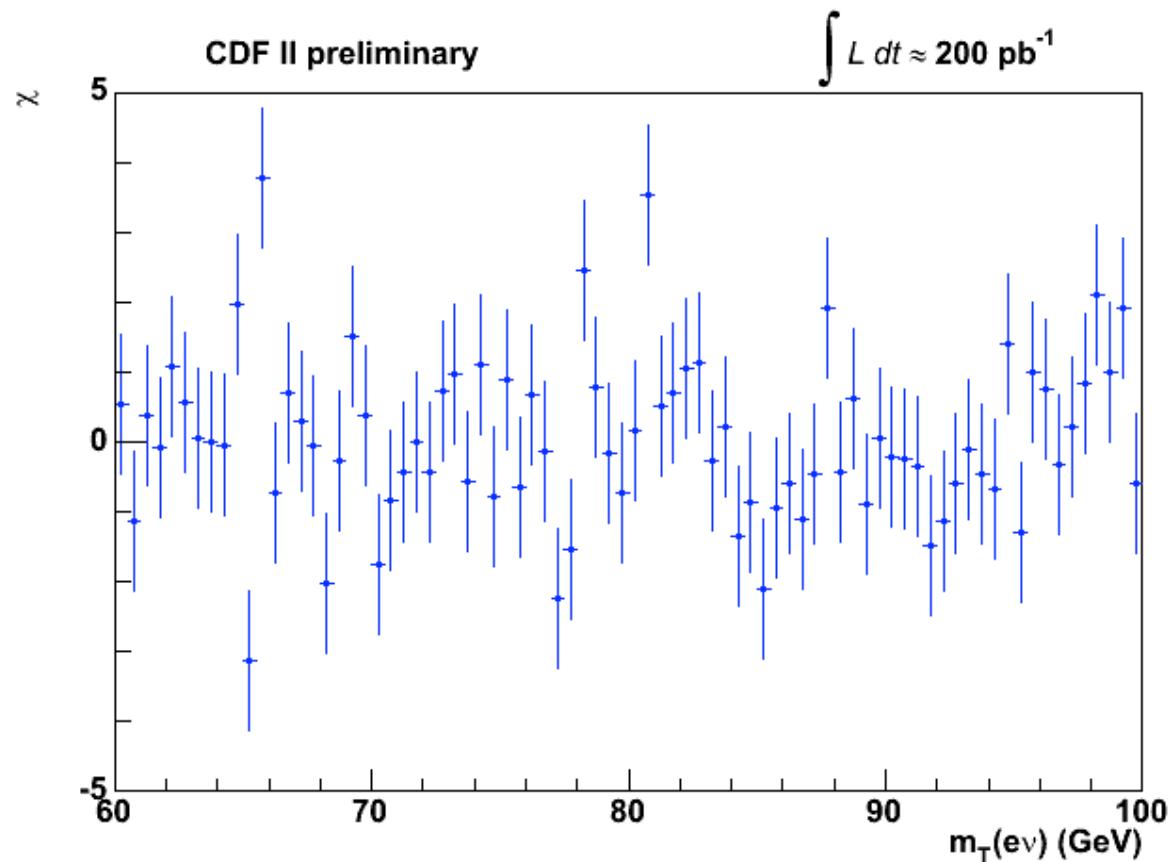


Backup Slides

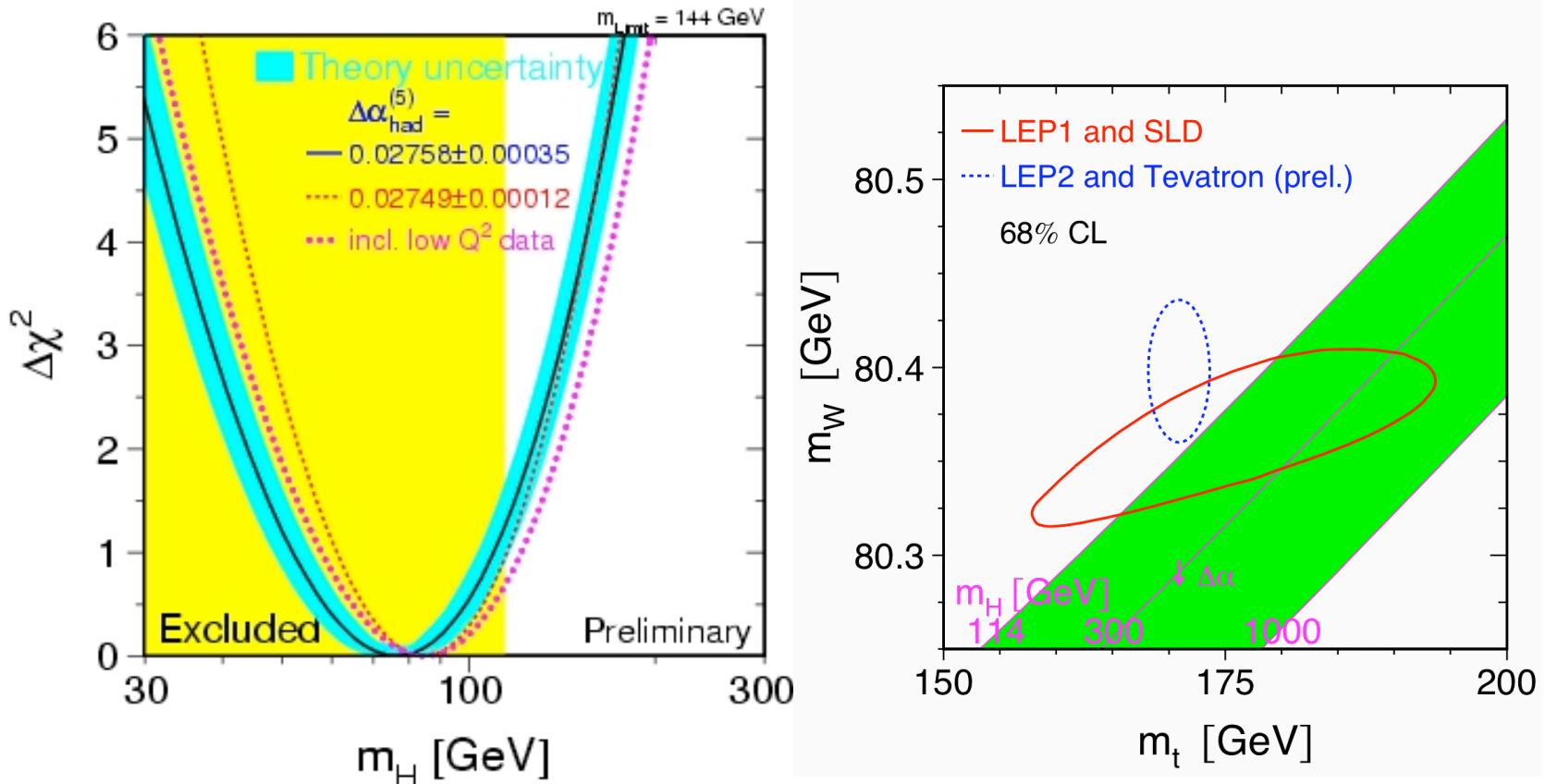
Systematic Uncertainty

CDF II preliminary				$L = 200 \text{ pb}^{-1}$				CDF II preliminary				$L = 200 \text{ pb}^{-1}$			
p_T Uncertainty [MeV]	Electrons	Muons	Common	p_T Uncertainty [MeV]	Electrons	Muons	Common	p_T Uncertainty [MeV]	Electrons	Muons	Common	p_T Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17	Lepton Scale	30	17	17	Lepton Scale	30	17	17	Lepton Scale	30	17	17
Lepton Resolution	9	3	0	Lepton Resolution	9	5	0	Lepton Resolution	9	5	0	Lepton Resolution	9	5	0
Recoil Scale	17	17	17	Recoil Scale	15	15	15	Recoil Scale	15	15	15	Recoil Scale	15	15	15
Recoil Resolution	3	3	3	Recoil Resolution	30	30	30	Recoil Resolution	30	30	30	Recoil Resolution	30	30	30
$u_{ }$ Efficiency	5	6	0	$u_{ }$ Efficiency	16	13	0	$u_{ }$ Efficiency	16	13	0	$u_{ }$ Efficiency	16	13	0
Lepton Removal	0	0	0	Lepton Removal	16	10	10	Lepton Removal	16	10	10	Lepton Removal	16	10	10
Backgrounds	9	19	0	Backgrounds	7	11	0	Backgrounds	7	11	0	Backgrounds	7	11	0
$p_T(W)$	9	9	9	$p_T(W)$	5	5	5	$p_T(W)$	5	5	5	$p_T(W)$	5	5	5
PDF	20	20	20	PDF	13	13	13	PDF	13	13	13	PDF	13	13	13
QED	13	13	13	QED	9	10	9	QED	9	10	9	QED	9	10	9
Total Systematic	45	40	35	Total Systematic	54	46	42	Total Systematic	54	46	42	Total Systematic	54	46	42
Statistical	58	66	0	Statistical	57	66	0	Statistical	57	66	0	Statistical	57	66	0
Total	73	77	35	Total	79	80	42	Total	79	80	42	Total	79	80	42

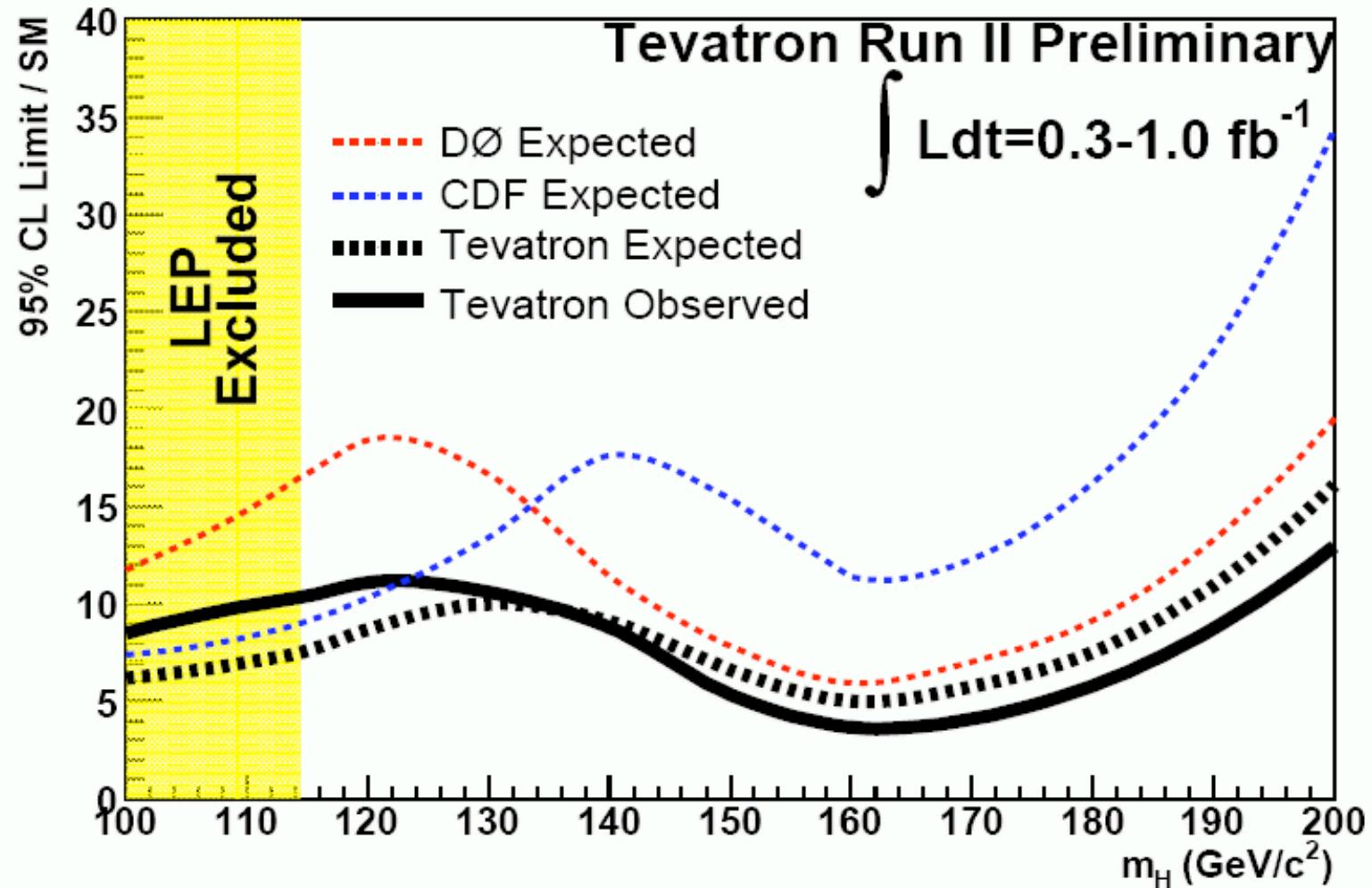
Signed χ



Latest Higgs Constraint



Higgs Sensitivity



Consistency Checks of Results

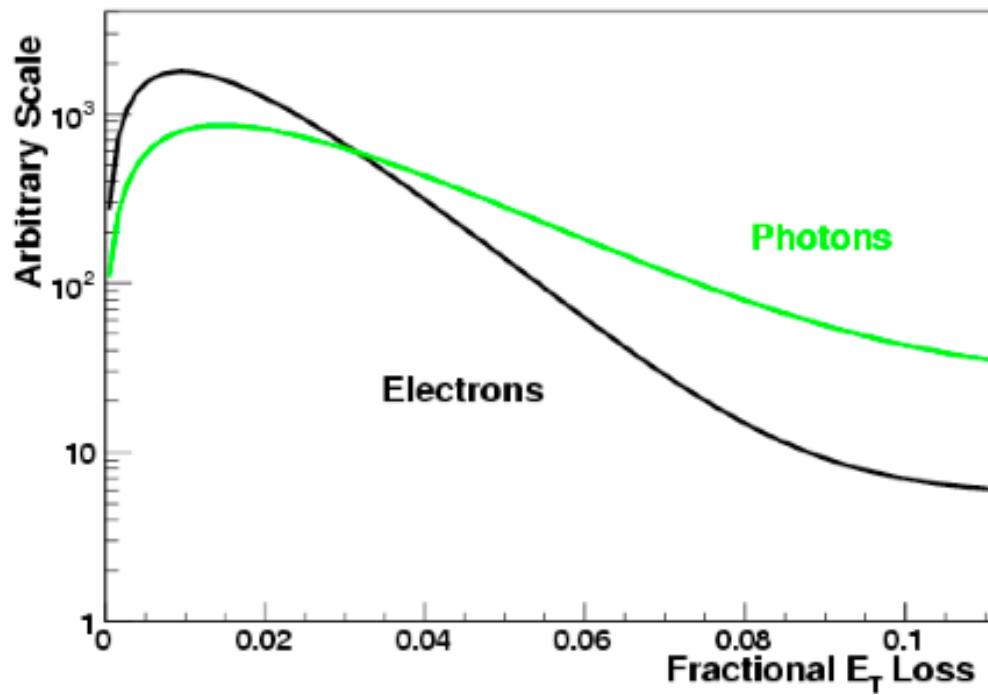
- Use BLUE method to combine results and check consistency
- List of obtained χ^2 and probabilities for several combinations:
 - two transverse mass fits: $\chi^2/\text{dof} = 3.2/1$, prob = 7%
 - charged lepton fits: $\chi^2/\text{dof} = 1.8/1$, prob = 18%
 - two MET fits: $\chi^2/\text{dof} = 0.6/1$, prob = 43%
 - all three fits for electrons: $\chi^2/\text{dof} = 1.4/2$, prob = 49%
 - all three fits for muons: $\chi^2/\text{dof} = 0.8/2$, prob = 69%
 - all six fits, both channels: $\chi^2/\text{dof} = 4.8/5$, prob = 44%

Tevatron Run I Uncertainties

	CDF μ	CDF e	D0 e
Statistics	100	65	60
Lepton energy scale	85	75	56
Lepton resolution	20	25	19
Recoil model	35	37	35
$p_T(W)$	20	15	15
Selection bias	18	-	12
Backgrounds	25	5	9
Parton dist. Functions	15	15	8
QED rad. Corrections	11	11	12
$\Gamma(W)$	10	10	10
Total	144	113	84

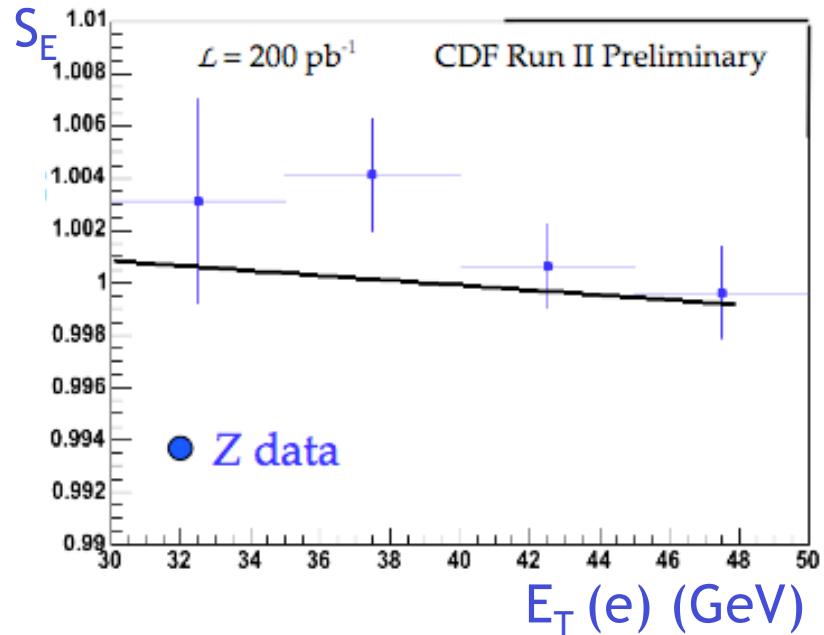
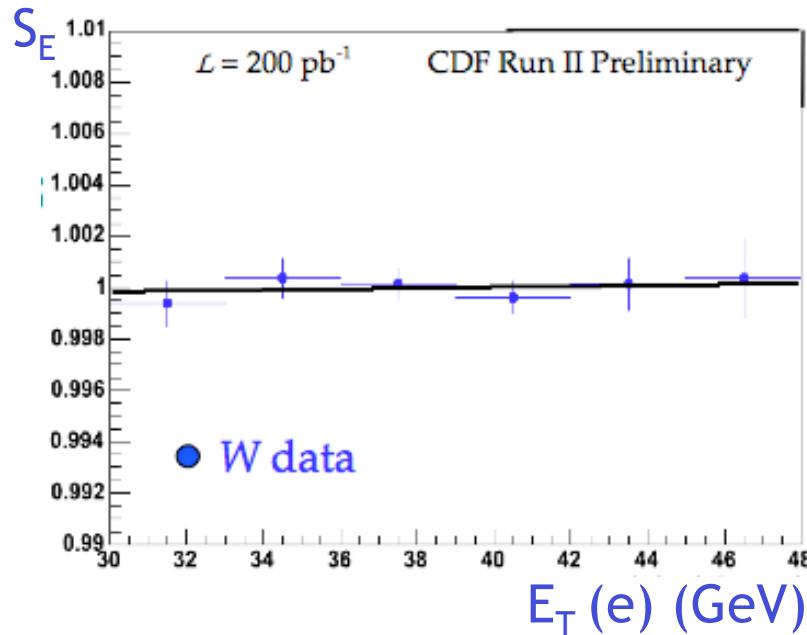
Energy Loss Model

- Use GEANT to parametrize energy loss in solenoid and leakage into hadronic calorimeter
- Energy loss in hadronic calorimeter
- Relevant for E/p lineshape



Measurement of EM Calorimeter Non-Linearity

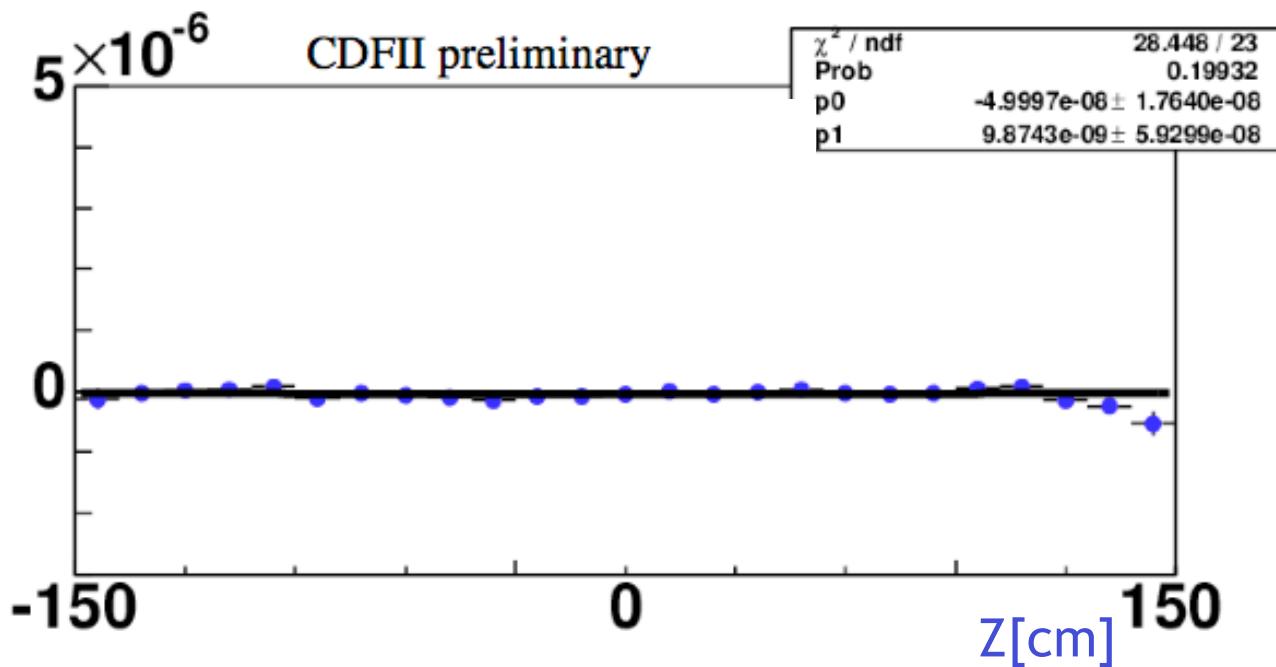
- Perform E/p fit-based calibration in bins of electron E_T
- Parametrize non-linear response as $S_E = 1 + \xi(E_T/\text{GeV} - 39)$
- Apply energy dependent scale to simulated electron and photon
- Tune W and Z data: $\xi = (6 \pm 7) \times 10^{-5}$



COT Wire Alignment

- Fit separate helices to cosmic ray tracks on each side
- Compare track parameters of the two tracks
- Measure of track parameter bias

Curvature:



Material Distribution

